# DEVELOPMENT OF LIGHTWEIGHT CONCRETE UTILIZING LOCAL MATERIALS

BY

**OSMAN MOHAMMED SABER**

A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

**KING FAHD UNIVERSITY OF PETROLEUM & MINERALS**
DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

**MASTER OF SCIENCE**

**In**

**CIVIL ENGINEERING**

**May 2014**

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

**DEANSHIP OF GRADUATE STUDIES**

This thesis, written by **OSMAN MOHAMMED SABER** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN CIVIL ENGINEERING.**

Dr. Salah U. Al-Dulaijan
(Advisor)

Dr. Mohammed Maslehuddin
(Member)

Dr. Shamsad Ahmad
(Member)

٢٠١٤/١/٢٦

Dr. Nedal T. Al-Ratrout
Department Chairman

26 OCT 2014

Dr. Salam A. Zummo
Dean of Graduate Studies

عمادة الدراسات العليا
DEANSHIP OF GRADUATE STUDIES

4/11/14

Date

بِسْمِ ٱللَّهِ ٱلرَّحْمَٰنِ ٱلرَّحِيمِ

In the Name of Allāh, the Most Gracious, the Most Merciful

*Dedicated*

*to*

*My Maternal Grandfather*

# ACKNOWLEDGMENTS

All praise be to Allah, *subhanahu-wa-ta'ala*, the Almighty who gave me the opportunity to accomplish my MS degree at King Fahd University of Petroleum and Minerals, and may the peace and blessings of Allah be upon his prophet, Muhammad (S.A.W).

With deep and indebted sense of gratitude, I would like to express my sincere thanks to my thesis advisor, Dr. Salah U. Al-Dulaijan for his invaluable support, guidance, continuous encouragement and all possible cooperation throughout the period of my research and preparation of thesis documentation. Working with him was a wonderful and learning experience, which I thoroughly enjoyed.

My sincere thanks and appreciation is due to the thesis committee members Dr. Mohammad Maslehuddin and Dr. Shamsad Ahmad for investing their time and their support, critical reviews and suggestions to improve this work.

Acknowledgement is due to the King Fahd University of Petroleum and Minerals for providing the financial support and world class facilities which made my life smoother and easier to devote myself fully in academic and research works. Especially, I am grateful to all the faculty and staffs of the Center of Engineering Research department at KFUPM.

I owe a deep sense of gratefulness to my numerous friends and colleagues whose presence and moral support made my entire stay at KFUPM enjoyable and fruitful.

Finally, I would like to express my profound gratitude to my parents and my siblings for their sacrifice, incessant prayers, love and support that motivated me to complete this work.

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# THESIS ABSTRACT (ENGLISH)


**NAME: OSMAN MOHAMMED SABER**

**TITLE: DEVELOPMENT OF LIGHTWEIGHT CONCRETE UTILIZING LOCAL MATERIALS**

**MAJOR: CIVIL ENGINEERING**

**DATE: MAY 2014**

The utilization of lightweight concrete in construction of infrastructure is greatly beneficial, in that, it is capable of assembling loadbearing elements of small cross sections and a corresponding reduction in the size of the foundation. Basaltic pumice (scoria), although porous but a potential lightweight aggregate, remains unexploited in the mountains of Makkah and Madina in abundance. Waste materials/Industrial byproducts such as oil ash and crumb rubber have opened avenues for their use in concretes.

This study was intended to explore the possibility of utilizing different lightweight local materials, such as scoria, polypropylene, oil ash and rubber, as aggregate to develop Lightweight Concrete (LWC). The mechanical, thermal and durability properties of concretes produced utilizing these materials individually, as well as in combination with others, were investigated. Results of this investigation show that these lightweight materials are capable of producing thermal resistant concretes of low to medium strength and corrosion resistance requirements. Recommendations were made on possible applications of the developed LWC.

**MASTER OF SCIENCE DEGREE**

**KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS**

**Dhahran, Saudi Arabia**

## THESIS ABSTRACT (ARABIC)

# ملخص الرسالة

**الاسم: عثمان محمد صابر**
**الرسالة عنوان : تطوير خرسانة خفيفة الوزن باستخدام المواد المحلية**
**التخصص: المدنيةالهندسة**
**تاريخ التخرج: مايو 2014**

استخدام الخرسانة خفيفة الوزن في بناء البنية التحتية هو مفيد إلى حد كبير، في ذلك ، أنها قادرة على تجميع عناصر حاملة من المقاطع العرضية الصغيرة و انخفاض مماثل في حجم القواعد. الحجر البزالتي ( سكوريا ) ، على الرغم من مسامية ولكن هذا الحجر خفيف الوزن ، ولا تزالوفرة من هذا الحجر غير مستغلة في جبال مكة المكرمة والمدينة المنورة هناك. مواد النفايات أو المخلفات الصناعية مثل رماد النفط و المطاط المقطع قد تكون هناك سبل لاستخدامها في الخرسانة .

ان الغرض من هذه الدراسة هو استكشاف إمكانية استخدام مواد مختلفة ومنتجة محليا خفيفة الوزن ، مثل سكوريا و البولي بروبلين ، ورماد النفط و المطاط ، والمقطع لجزء من الحجارة لتطوير خرسانة خفيفة الوزن ( LWC ) . ان الخواص الحرارية وديمومة الخرسانة باستخدام هذه المواد بشكل فردي ، وكذلك بالاشتراك مع مواد اخرى والميكانيكية، وسوف تقيم في هذه الدراسة .نتائج هذا التحقيق تبين أن هذه المواد الخفيفة الوزن قادرة على إنتاج خرسانة مقاومة للحرارة وذات قوة متباينة للتآكل. وقدمت توصيات بشأن التطبيقات الممكنة لل LWC المطورة.

**درجة الماجستير في الهندسية العلوم**
**جامعة الملك فهد للبترول والمعادن**
**الظهران - 31261**
**المملكة العربية السعودية**

# CHAPTER 1

# INTRODUCTION

## 1.1 Lightweight Concrete

Concrete is the most predominantly used construction material in Saudi Arabia. Normal weight concrete (NWC) is the main concrete type for structural applications despite its relatively heavy weight and weak thermal properties. It is uneconomical since it constitutes a huge portion of the structural loads. To reduce the dead loads and hence, to make the structures economical, lightweight ingredients can be used in concrete. But, the resultant concrete should also be capable of retaining adequate strength for use in structural members. This has sparked the need to develop lightweight concrete (LWC).

LWC is a conglomerate of cement and lightweight aggregates. The bulk density of LWC is in the range of 1400 and 2000 kg/m$^3$ compared to a range of 2200 to 2600 kg/m$^3$ for NWC. The advantages of LWC are: (a) Reduction in the size of structural components due to reduced dead loads, which may result in a reduction in the quantity of cement and a possible reduction in reinforcement, (b) Utilization of cheap and smaller transporting and handling equipment due to smaller and lighter pre-cast elements, (c) Reduced size of footing and larger space availability as a result of reduction in the size of slabs, beams and columns, (d) Enhanced fire resistance and (e) High thermal insulation.

But, environment protection is perhaps the most significant potential advantage of the use of LWC. If the natural resources and industrial waste products are utilized as raw materials needed for production of LWC, it will boost the economy and environment of the country. Also, the production of large quantity of cement is a major contributor to $CO_2$ emissions. The environmental impacts of the Portland cement due to energy usage, consumption of resources and $CO_2$ emissions is very high during its manufacture. One ton of Portland cement produced, consumes approx. 1.5 tons of raw materials and as a result, emits one ton of $CO_2$ into the environment during production, with similar amount of $CO_2$ emissions from energy sources [1]. The use of LWC, which significantly reduces the quantity of cement on a large scale, will help in the reduction of greenhouse gas emissions.

LWC has been used earlier for structural purposes. Completed during the 1920's, Park Plaza Hotel in Kansas City, USA, was the first structure built with LWC [2]. The long term durability of LWC can be exceptionally high, as is evident by the construction of a 7500-ton lightweight concrete ship, USS Selma, built during the First World War [3-4]. In general, the advantage of lower foundation costs and reduced dead loads can offset the higher unit cost of lightweight structural concrete, where existing structures are being expanded or altered. For example, four stories were added to an existing Cleveland department store without modifying the foundation [5]. In bridges, a significant portion of the load carried by pre-stressed concrete girders is the self-weight of the girders and deck [6-8]. These girders and decks are generally manufactured using NWC. Use of structural LWC offers the benefit of reducing the weight and size of the structure itself. Along with huge economic benefits, these size and weight reductions facilitate handling during shipping and construction or replacement of bridge elements [9]. LWC has strengths comparable to NWC, yet is typically 25-35% lighter [10]. Since the mass of the buildings and structures are proportional to the seismic loads influencing the buildings and structures, the risk of earthquake damage can be reduced by installing LWC structures [11].

The many advantages of LWC make it a captivating topic for researchers to identify new materials and techniques to use it; and many contractors, architects and engineers realize the inherent advantages and cost savings offered by LWC, as evident from the many remarkable LWC structures found all over the world.. The advantages include saving on scaffolding and formwork, foundation cost, savings of reinforcement, transport cost, better sound absorption and thermal insulation than ordinary concrete, better anti-condensation properties, lower tendency to buckle or warp owing to differential temperature gradients, durability, better frost and fire resistance, and heat isolation [12]–[14].

LWC can be developed by using: (a) gassing agents, such as foaming agents or aluminium powder, (b) mineral aggregates like vermiculate, clay, expanded shale, pumice, scoria, slate and perlite, or (c) plastic granules as aggregate, e.g., polypropylene, expanded polystyrene foam, or other polymer materials [15]. Different wastes can also be utilized as a source of raw materials, such as crumb rubber. Commercial production of raw materials are carried out under different trade names by countries like Germany, USA, Russia, UK and Poland [16].

A rise in demand for use of LWC in many applications of modern industry has been observed owing to economic and practical considerations. While some research on the properties of LWC has been conducted in other parts of the world, data are lacking on their development in the Kingdom. Consequently, the aim of the reported study was to develop

LWC utilizing local materials as much as possible. The developed LWC should have high thermal resistance and it should be durable and economical.

## 1.2 Significance of this Research

The material that is most widely used by the construction industry is cement. Cement is the principal ingredient in concrete. Manufacturing of cement is a source of greenhouse gas emissions. Nowadays, there is an increasing demand for concrete worldwide. Hence, there is a need to meet the demand without a corresponding increase in greenhouse gases [17]. If mechanical and durability properties of LWC comparable with NWC can be achieved, the latter concrete can be replaced with the former one. LWC is characterized by its low density. Therefore, structures made with LWC will have slender structural members and lesser foundation depth. This will decrease the overall consumption of cement in a structure which may ultimately lead to a reduction in the greenhouse gas emissions. While some research has been conducted in the past using natural and artificial aggregates in the other parts of the world there is a need to develop LWC utilizing local natural and industrial byproducts. Materials, such as scoria, which is abundantly available in the Western part of the Kingdom of Saudi Arabia, can be utilized for the production of LWC. Furthermore, crumb rubber obtained by recycling waste materials and industrial byproducts, such as oil fuel ash can be used. Therefore, the consumption of waste materials that are generated in abundance during manufacture of building and other materials in the Kingdom of Saudi Arabia is a noble task that will certainly lead to a greener environment [17]. Further, the usage of these waste cheap materials in concrete will produce economical building materials. Hence, there is a growing need to utilize locally available waste materials in concrete to overcome the environmental problems and develop LWC. Historically, LWC is used for both non-structural and structural applications. Specific characteristics are desirable in LWC to meet the performance and strength requirements, for its application as a structural material. Thus, there is a need to study the durability characteristics and mechanical and thermal properties to ascertain the suitability of LWC for recommending it for a specific application (non-structural or structural) [18].

## 1.3 Objectives

The overall objectives of the proposed study were to develop mix design for durable LWC utilizing a combination of local natural materials and/or industrial byproducts. The specific objectives were the following:

I. Develop LWC utilizing local natural materials and/or industrial byproducts,

II. Assess the mechanical and thermal properties, and durability characteristics of the developed LWC, and

III. Provide recommendations on the avenues of application of the developed LWC.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Definition of Lightweight Concrete

Lightweight concrete (LWC) is a conglomerate of cement and lightweight aggregates (LWA). It has a bulk density ranging between 300 and 2,000 kg/m$^3$ compared to a value of 2,200 to 2,600 kg/m$^3$ of the normal weight concrete (NWC). On the basis of its bulk density and compressive strength, LWC is broadly divided into the following categories:

**Thermo insulating lightweight concrete**: bulk density: 300–800 kg/m$^3$; compressive strength: 0.5 – 7 MPa. This type of LWC is used as filling material or as an insulating coating.

**Low strength lightweight concrete**: bulk density: 800–1,400 kg/m$^3$; compressive strength: 7 – 16 MPa. This type of LWC is used in structures that do not require particular performances from strength point of view. At the same time, it guarantees an acceptable level of thermal comfort.

**Structural lightweight concrete**: bulk density: 1,400 – 2,000 kg/m$^3$; compressive mechanical strength: > 17 MPa. This type of concrete is usually manufactured with synthetic aggregates. The reduced bulk density of this type of LWC is due to the addition of a void system within the cementitious conglomerate. This can be achieved by the following three methods:

i. Utilizing natural or artificial LWA with high porosity.
ii. By introducing small polystyrene balls in concrete in lieu of normal aggregates, partially or totally.

iii. By adding to the mixture a substance that is able to develop gases in an alkaline environment.

LWA used for the manufacture of LWC is characterized by a highly porous microstructure and, consequently, a low bulk density (< 1,200 kg/m$^3$). LWA can be natural (pumice, diatomite, etc.) or artificial (expanded aggregates), the latter obtained by natural or artificial materials after a processing cycle that is able to create a cellular or highly porous structure. The natural raw materials (usually clay or shale) contain substances able to develop gases during the heating stage at temperatures close to those at which the material begins to soften. In these conditions a very viscous liquid phase is formed and it is able to entrap the gas developed and thus allowing the aggregates to expand.

This process is carried out in large rotating furnaces (diameter around 4.5 m; length around 70 m) at temperatures that can even reach up to 1,300°C. After cooling, the product occurs as spherical aggregates with an inner cellular microstructure and a glassy surface providing the aggregate with a good mechanical strength and low water absorption.

The use of LWC has many advantages. These include: (a) Reduction in the dead load that may result in reduced size of structural components. This may result in a reduction in the quantity of cement and a possible reduction in reinforcement. (b) Lighter and smaller pre-cast elements needing smaller and less expensive handling and transporting equipment. (c) Reduction in the size of columns, beams and slabs that result in larger space availability and reduced size of the footings. (d) High thermal insulation. (e) Enhanced fire-resistance. But perhaps the most significant potential advantage of the use of LWC is the environmental protection. If the raw materials needed for production of LWC are derived from industrial waste products, the environment and economy of the country stands to benefit. Also, it will result in a significant reduction in the greenhouse gas by reducing the need of large quantities of cement whose production is a major contributor to $CO_2$ emission.

While some information is available on the manufacture and use of LWC in other parts of the world, there is a need to develop such a concrete in the Kingdom utilizing local materials and/or synthetic materials.  Particular emphasis should be placed on the use of local natural and industrial byproducts.

Low density of the aggregate due to porosity has been looked upon as beneficial to concrete. Porosity can be utilized to store moisture for use in internally cured concrete [19-20]. It has been known since the 1960's that as the cement hydrates in concrete, moisture can be provided to it by the LWA [21]. Bloem, [22] reported that ''high absorption LWA may have the beneficial effect of supplying curing water internally''. Philleo discussed the potential for improved strength and durability due to this internal curing [23]. There is circumstantial evidence of reduced plastic shrinkage during high rise construction in LWA mixtures, as reported by Holm et al. [24]. Since there has been increased observances of cracking in higher strength lower water/cement ratio concrete, there is a need to develop LWC through the use of LWA, to improve the curing in concrete [20, 25-27].

Volume fraction and properties of aggregate mainly affect the compressive strength of concrete as demonstrated by Yang and Huang [28]. But for some LWAs, Lydon pointed out that the compressive strength is directly proportional to density and also depends on the type of aggregate [29]. The high internal porosity of the LWA is an essential characteristic and results in a low apparent specific gravity. The strength of the lightweight particles of coarse aggregate may be the limiting factor affecting concrete strength, since LWA is very weak [30]. The interaction of the lightweight aggregates and the paste matrix is different from that of normal concrete [31].

The available literature on Alkali Silica Reaction (ASR) in mortars and concretes prepared by LWA is somewhat contradictory. Some researchers have studied ASR in mortars and concretes prepared by both natural and artificial LWAs. They reported that there are practically no signs of this reaction in such concretes [32-33]. However others [34-35] have stated that some structures had to be either extensively repaired or demolished due to the significant damage to the cement composites owing to ASR. Still others have concluded that only some LWAs (expanded glass, perlite, and expanded clay) are affected by ASR, but do not show any harmful effects, such as efflorescence and/or expansion [36]. It is supposed that the gel produced is gathered in the pores of the glassy phase of LWAs, which is more readily carbonated, less prolific and more “sticky” [37], and thus indirectly prevents expansion.

All over the world, research has been done on a large number of artificial (such as slate, vermiculite, expanded shale, slag and perlite) or natural ( such as scoria, oil palm shells, diatomite, bottom ash, saw dust and pumice) aggregates to produce concrete and mortar [38-47]. The cost of such concretes can be significantly reduced if natural LWAs are used instead of processed artificial aggregates. Finding improved and new ways to develop LWC using natural volcanic aggregates (such as ash, scoria) is becoming widespread and low-cost construction can be achieved by using such construction materials [38, 45-46]. Sustainable construction and less greenhouse gas emissions are possible if volcanic materials are used in blended cement production as replacement of Portland cement [38, 45-46].

The use of waste material as aggregate in LWC can help achieve economical and environmental benefits.

Generally, the constitution of aggregates in Portland cement concrete is about 70 to 80% by volume. Due to this, the elastic modulus of concrete is highly influenced by the aggregates. Aggregates are also expected to have an important influence on other properties as well [2].With a wide range of LWAs available for concrete, there is a need for a better understanding of the influence of the properties of LWAs on the compressive strength and elastic modulus of concrete.

Concrete can be produced for suitable strength values and in a wide range of unit weights for different fields of applications utilizing natural or artificial aggregates available in different parts of the world [48]. One of the main objectives of LWC development is to produce a material which has good thermal insulation. But there are various other advantages of LWC due to its lightness, such as, smaller cross-sections owing to reduced dead loads and better durability [49-50].

## 2.2 Materials Used in LWC

### 2.2.1 Basaltic Pumice (Scoria)

Several natural and artificial aggregates have been utilized to prepare LWC. Scoria is one of the natural aggregates that can be utilized for the production of LWC. It is a volcanic rock that may or may not contain crystals and is formed of vesicular fine to coarse fragments. It is typically dark in color (generally dark brown, black or purplish red), and basaltic or andesitic in composition. Scoria is relatively low in mass, but in contrast to pumice, scoria has a specific gravity greater than 1, and sinks in water.

Bulk density of scoria samples, tested according to ASTM C-567, is about 866 $kg/m^3$ for rodded density, and an average value of 776 $kg/m^3$ for loose density. Maximum dry loose unit weight, according to ASTM C-330, C-331 and C-332, is 880 $kg/m^3$ for coarse aggregate and 1040 $kg/m^3$ for combined coarse and fine aggregate [51]. Figure 2.1 shows the relation between rodded and loose density of scoria samples.

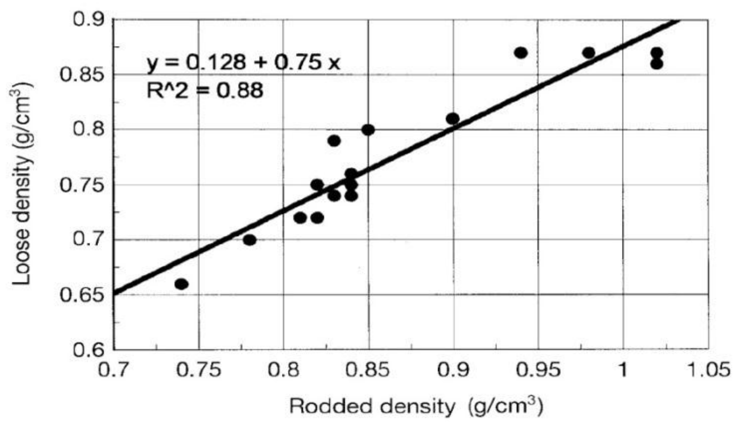


**Figure 2-1: Relation between rodded and loose density of scoria samples.**

Figure 2.2 shows the bulk specific gravity (dry), bulk specific gravity (saturated surface dry) and apparent specific gravity values of scoria samples retained on sieve #4 (4.75 mm; coarse aggregate) and the material passing it (fine aggregate). These were determined according to ASTM C-127 and C-128, respectively [51].

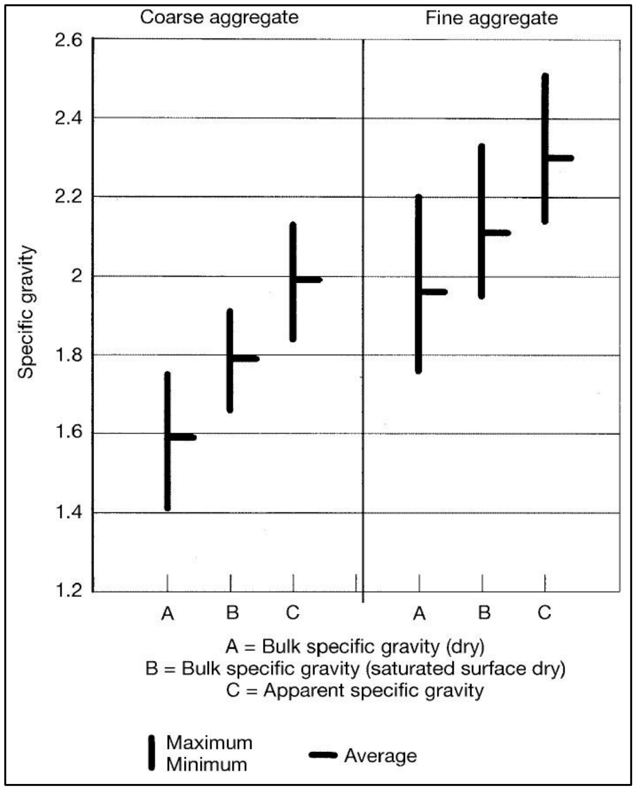


**Figure 2-2: Range of values of different specific gravities of scoria.**

Scoria can be utilized in several industrial applications, including the manufacturing of thermal-insulating concrete, lightweight concrete and building blocks, especially where energy needs to be conserved and the weather is harsh. It can be seen as a source for pozzolan to manufacture Portland-pozzolan cement additive and can provide material for precast concrete units [51]. Some other applications are utilization as low cost fillers in paint, absorbents and other architectural applications [7].

Lava fields called Harrats cover an area of 180 000 $km^2$ in western Saudi Arabia. These Harrats extend in the north-south direction and contain volcanic basaltic rocks. Although there is a widespread presence of basaltic volcanic scoria deposits in and around the scoria cones in the Harrats, very few occurrences have been evaluated and still fewer have been exploited. There is a need to investigate the quarries from this region to assess their industrial utilization [7].

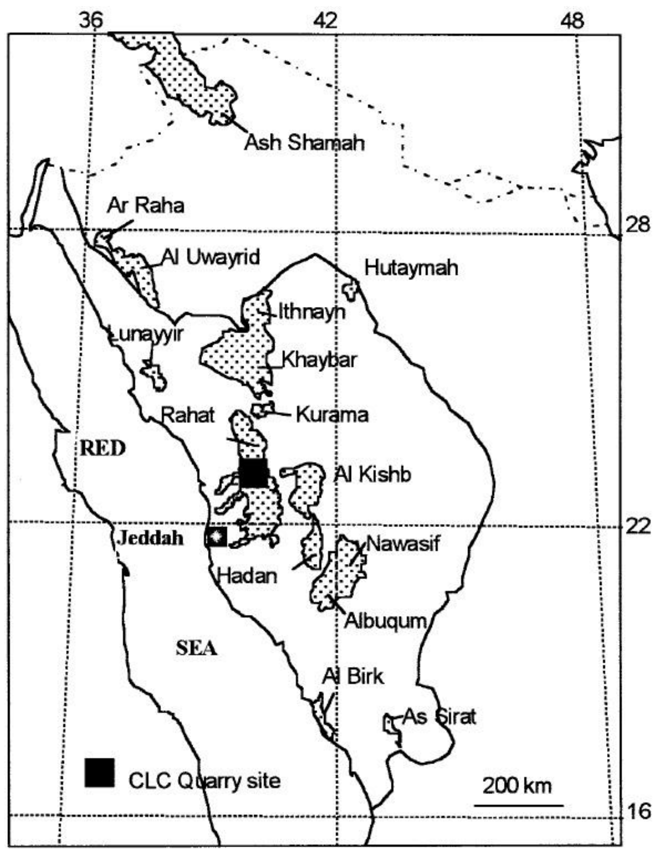


**Figure 2-3: Scoria quarries in western region of Saudi Arabia.**

In an attempt to study the engineering characteristics of scoria as a LWA, central Harrat Rahat was selected as a source for the natural aggregate. The grading analysis indicated that scoria needs to be processed before use. The physical properties, such as specific gravity, bulk density, absorption, deleterious material content and petrography were found to be acceptable by ASTM standards. The porosity is high and some pore spaces are not interconnected [51]. Also, due to larger water absorption of scoria, the concretes made with different percentages of scoria need larger water-cement ratio for suitable workability.

Moufti et al. [7] used scoria as lightweight fine and coarse aggregates in different proportions to prepare cubes. They found the compressive strength and thermal conductivity values of these cubes to be acceptable according to the requirement of structural concrete. Pozzolanic activity was tested according to the Italian standards and found to be acceptable. The strength activity index with Portland cement and the effectiveness of scoria admixture in controlling alkali-silica reactions were tested according to ASTM standards.

The results satisfied the ASTM requirements as cement additive. Satisfactory results were obtained when scoria was tested for utilization as heat-insulating material. This fact suggests it could be utilized in the manufacture of building blocks. It is recommended to evaluate the other scoria deposits, exploit the economically feasible ones and utilize them for different industrial applications. The manufacturing of heat-insulating concrete or building blocks using scoria is of prime importance as an energy saver [7].

Arakelyan et al. [52] showed that, when compared to concretes with rock aggregates, the impermeability of the lightweight concretes with natural porous aggregates is appreciably higher [53-54]. A cement crust forms around porous aggregates as a consequence of their absorption properties, which plugs the surface pores, and this lowers the permeability and increases the frost resistance of this material. The life of such lightweight concrete is no less than that of ordinary concrete as shown by field observations of structures during 15 years of operation.

Lightweight concrete utilizing scoria was used in pressure chambers, tunnel linings and penstocks, and aboveground and underground parts of the Gyumush hydroelectric power station [52].

Research conducted by Kilic et al. [8] used basaltic-pumice (scoria) as LWA. A control LWC mixture containing normal Portland cement as binder was modified by replacing 20% cement with fly ash and 10% cement with silica fume. Density and slump workability of the fresh concrete mixtures, and compressive and flexural tensile strength tests after curing at 65% relative humidity and 20 $^{0}$C temperature, were carried out and compared with two NWCs. It was reported that scoria can be used to produce structural lightweight concrete (SLWC) and the authors recommended the use of mineral additives for the production of SLWC [8].

### 2.2.2 Limestone

Limestone, composed mostly of mineral calcite, is a very common sedimentary rock of biochemical origin. ‘Dirty limestone’ is filled with lots of minerals other than calcite and sand. Limestone can be found in the beds of evaporated seas and lakes and from the shells of sea animals. Limestone is an important rock and is an excellent building material for humid regions. Since it is easily weathered by acidic conditions, this rock is not as strong as sandstone. Limestone is the primary source of lime for cements. Significant quantities of limestone are quarried all over the world and crushed for use as road ballast. High-calcium limestone contains more than 95% of calcium carbonate. Recrystallized limestone is usually used as building and decorative stone and can take good polish. Limestone has a density of 2,500–2,650 kg/m$^3$, water absorption of less than 1 %, hardness of 3–4 on Moh's scale , and compressive strength of 180–210 MPa [55].

Sajedi et al. [55] produced high-strength structural lightweight concrete (HSSLWC) by using Lightweight expanded clay aggregate (LECA), which reduces the weight of the concrete. To increase strength and reduce porosity, limestone was used along with chemical and mineral admixtures. Indirect tensile, flexural and compressive strength tests were carried out on the specimens. Some specimens were kept in open air to investigate the effect of curing on the compressive strength. Lightweight structural concrete (LWSC), with a dry density in the range of 1610-1965 kg/m$^3$ and compressive strength in the range of 34-67MPa was achieved using Leca, based on cube specimens with 100mm side length. Whenever mixed with lightweight concrete, limestone improved its mechanical properties.

It is observed that there is an increase of upto 40% in flexural strength results, by using limestone in LWC, without a noticeable increase in the specific gravity [55].

Author suggests implementation of mix design method of high-performance self-compacting concrete for developing LWC since using conventional mix design methods would result in high material segregation, as well as reduced strength due to low density of aggregate [56].

### 2.2.3 Oil Ash

Another local industrial byproduct that could be utilized in the production of LWC is oil fuel ash (OA). OA is generated during the burning of oil in power generation plants. This is a very fine ash and most of it passes # 200 sieve. The consumption of oil reaches 1 million bpd of crude during summer months and it is likely to increase to 8 million bpd by 2030 if there are no improvements in energy efficiency [9]. It is presently disposed off as a waste material, posing environmental and storage problems. Initial screening tests conducted at KFUPM indicated that the pozzolanic activity of 5 to 20% OA cement mortar was less than that of control concrete containing 100% cement [57]. Since the density of OA is low (1.3) it is desirable to study the possibility of utilizing it in the production of LWC. Large quantities of OA could be incorporated in the production of LWC [17].

OA was found to be a non-pozzolanic material, composed of a high proportion of unburned carbon and shown to have a very high specific surface area together with a much lower relative density to that of cement [58].

Various tests were performed on OA for investigating its reutilization as replacement of Portland cement in low grade concretes for use in concrete masonry units and as flowable backfilling material. A cement replacement limit of 30% for flowable fill concrete and 20% for concrete masonry units was recommended by Camilleri et al. [58].

Although OA has not been used extensively in concretes compared to fly ash, the benefits of using OA could be far greater since it may allow for a reduced amount of cement to be used, [59-60]. But the water requirements and the setting times increased drastically as the cement replacement quantity was increased [61]. As a result of increased water demand, the strength of the OA replaced specimen was reduced compared to the control concrete. Nonetheless, the 28-90 day compressive strength gain for OA replaced samples was better than that of the control mix [58].

### 2.2.4 Crumb Rubber

Another product that has been used for the production of LWC is rubber. The growing problem of waste tyre disposal in Saudi Arabia can be alleviated if new recycling routes can be found for the surplus tyres. One of the largest potential routes is in construction, but usage of waste tyres in civil engineering is currently very low. Scrap tires can be granulated to produce crumb rubber, which has a granular texture and ranges in size from very fine powder to coarse sand-sized particles. Due to its low specific gravity, crumb rubber can be considered a lightweight aggregate.

Kew et al. [62] investigated the potential of incorporating recycled rubber tire chips into Ordinary Portland Cement (OPC) concrete and compared its strength and workability properties with plain concrete. Rubber aggregates coated with cement paste and plain rubber aggregates were used. Reduction in compressive strength coupled with lower unit weight and workability were observed, although it benefited on flexural strength. The potential of rubber as aggregate in concrete block and LWC was discussed.

Use of crumb rubber and shale ceramsite to produce flexible concrete was experimented by Wang et al. [63] in order to explore the relationship between the microstructure features and mechanical properties, with a purpose to improve the flexibility of concrete for specific applications. Elastic modulus and compressive strength of the rubberized LWC were determined. An increase in the crumb rubber dosage showed weakening of the aggregate-cement bond. It was reported that an adjustment in the crumb rubber dosage can effectively improve flexibility of LWC.

Mohammed et al. [64] prepared 64 trial mixtures using crumb rubber in different percentages as replacement of fine aggregate to study the development of crumb rubber hollow concrete block (CRHCB). Compressive strength, electrical resistivity, transmission loss, acoustic absorption and thermal conductivity tests were conducted on hardened concrete. The authors suggest that CRHCB can be produced as lightweight hollow blocks and load-bearing hollow blocks. It was reported that compared to conventional hollow block, CRHCB performed better in acoustic, electrical and thermal properties [64].

The one day-aged compressive strength and fresh properties of controlled low-strength rubber lightweight aggregate concrete (CLSRLC) and controlled low-strength rubber concrete (CLSRC) were studied by Wang et al. [65]. Each of the mix proportions (rubber replacements of 0%, 10%, 20%, 30% and 40%) resulted in slump flow, slump and tube flow values greater than 400, 190 and 150 mm, respectively. CLSRLC fresh properties were found to be superior to CLSRC. The unit weight decreased by approximately 69 $kg/m^3$ and the initial setting time was increased by approximately 35 min, for every 10% increase in the amount of rubber particles. Also, increasing rubber had a negative impact on the compressive strength. Optimum rubber replacement of 20% was suggested.

Pierce et al. [66] observed that flowable fill is rapidly gaining application and acceptance in construction, particularly in utility earthworks and transportation, owing to its ability to level and compact by itself. A study was conducted to explore the feasibility of using crumb rubber as a replacement for sand in flowable fill to produce a lightweight material. For this purpose, fluid and hardened state properties of nine flowable fill mixtures were measured. Results indicate that crumb rubber-based flowable fill can be used in a substantial number of construction applications, such as trench fills, foundation support fills and bridge abutment fills.

Wang et al. [67] observed that by adding rubber particles to LWA concrete, shrinkage rate increased, but when polymer was mixed, shrinkage rate decreased dramatically. When rubber particles were added, Microstructure analysis indicated that interface transition zone (ITZ) bondage between the rubber particles and cement matrix was poor, but when polymer was added, the ITZ structure of concrete improved. Therefore, addition of polymer is recommended while using rubber particles, to improve shrinkage performance and cracking resistance of concrete.

### 2.2.5 Polypropylene

Polypropylene (PP), also known as polypropene, is a thermoplastic. Polypropylene is made from the monomer propylene, is rugged and unusually resistant to many chemical solvents, bases and acids. It is normally tough and flexible. This allows it to be used as an engineering plastic. It is reasonably economical. It is often opaque or colored. It has good resistance to fatigue. Hydrocarbon slurry or suspension, bulk slurry and gas phase are the three manufacturing processes to produce polypropylene.

In 2008, the global market for polypropylene had a volume of 45.1 million metric tons, which led to a turnover of about $ 65 billion (~ €47.4 billion). Polypropylene is the second most important plastic with revenues expected to exceed US$145 billion by 2019. The demand for this material was growing at a rate of 4.4% per year between 2004 and 2012.

Polypropylene beads were used in the mixture proportioning and coarse pumice aggregate was used to develop lightweight concrete by Farnam et al., [68]. Fibers were added to increase the energy absorption and low ductility of the LWC. Specimens 150 mm diameter and 60 mm high were subjected to velocity impact load (according to the standard of ACI 544-2R "impact test on fiber reinforced concrete") to study their impact behavior. Also, a numerical simulation was performed to analyze the test specimens under impact loadings using the LS-DYNA finite element software. Fiber reinforced LWC fared well when compared to NWC under impact loading.

# CHAPTER 3

# EXPERIMENTAL PROGRAM

This chapter addresses the materials and experimental methods utilized in this study. This research focuses on the production of LWC using locally available industrial byproducts, natural and artificial aggregates, (i.e., OA, Scoria, Limestone, Crumb Rubber and Polypropylene). To achieve the objectives, the following phases were followed. First phase was to procure the concrete ingredients. In the second phase, preparation of specimens was carried out and in the third phase, testing of specimens was done to ascertain the mechanical, durability and thermal properties. In this chapter, all these three phases are discussed thoroughly.

## 3.1 Materials

### 3.1.1 Cement

Ordinary Portland cement conforming to ASTM C 150 Type I with a specific gravity of 3.15 was used in all the concrete mixtures. Sufficient amount of cement was procured and stockpiled safely to prevent its hardening. The chemical composition of the cement is shown in Table 3.1.

**Table 3-1: Chemical and mineralogical composition of cement**

| Constituent | Weight % |
|---|---|
| $SiO_2$ | 20.52 |
| $Fe_2O_3$ | 3.80 |
| $Al_2O_3$ | 5.64 |
| CaO | 64.35 |
| MgO | 2.11 |
| $Na_2O$ | 0.19 |
| $K_2O$ | 0.36 |
| $SO_3$ | 2.10 |
| Loss on ignition | 0.70 |
| Alkalis ($Na_2O$+0.658 $K_2O$) | 0.43 |
| $C_3S$ | 56.70 |
| $C_2S$ | 16.05 |
| $C_3A$ | 8.52 |
| $C_4AF$ | 11.56 |

### 3.1.2 Aggegates

#### 3.1.2.1 Fine Aggregate (sand)

Dune sand with water absorption of 0.6% and specific gravity of 2.56 was used as the fine aggregate. Oil ash and crumb rubber were also used as a replacement (10-20%) of sand in some mixes. Properties of these aggregates will be discussed in detail in the following sections.

#### 3.1.2.2 Coarse Aggregates

The specimens were prepared utilizing a combination of one or more of the lightweight/normal coarse aggregates, such as Scoria, crushed Limestone and

Polypropylene beads. Scoria and crushed limestone with four aggregate sizes of 12.5 mm (½ inch), 9.5 mm (3/8 inch), 4.75 mm (3/16 inch), and 2.36 mm (3/32 inch) were used. Properties of these aggregates will be discussed in detail in the following sections.

### 3.1.3 Other Materials

#### 3.1.3.1 Oil Ash

OA was procured from the Saudi Electricity Company power plant in Shayba, Saudi Arabia. The specific gravity and absorption of OA are 0.6 and 1.5%, respectively. The chemical composition of OA is shown in Table 3.2.

**Table 3-2: Chemical composition of OA**

| Constituent | Weight % |
|---|---|
| $SiO_2$ | 1.65 |
| CaO | 0.45 |
| $Al_2O_3$ | < 0.10 |
| $Fe_2O_3$ | 0.47 |
| MgO | 0.48 |
| $K_2O$ | 0.03 |
| $Na_2O$ | 0.53 |
| $V_2O_5$ | 2.65 |
| Sulfur | 9.6 |
| $Na_2O + (0.658K_2O)$, % | 0.55 |
| Loss on ignition | 60.6 |
| Moisture % | 5.9 |

#### 3.1.3.2 Limestone

Limestone was obtained from a quarry in Abu Hadriyah, Eastern Province, Saudi Arabia. The physical properties of limestone are shown in Table 3.3.

**Table 3-3: Physical properties of limestone aggregate**

| Aggregate type | Specific gravity | Absorption (%) | Fineness Modulus | Unit weight ($kg/m^3$) |
|---|---|---|---|---|
| Limestone | 2.6 | 1.1 | 3.23 | 1845 |

The chemical composition of limestone is shown in Table 3.4 and additional properties are shown in Table 3.5.

**Table 3-4: Chemical composition of limestone aggregate**

| Constituent | Weight % |
|---|---|
| CaO | 54.97 |
| $SiO_2$ | 0.01 |
| $Al_2O_3$ | 0.17 |
| $Fe_2O_3$ | 0.05 |
| $SiO_2+Al_2O_3+Fe_2O_3$ (>=70) | 0.23 |
| MgO | 0.64 |
| Loss on ignition | 43.66 |
| Fineness by Blaine ($cm^2/g$) | 856 |
| Specific gravity | 2.6 |

**Table 3-5: Additional properties of limestone aggregate**

| | |
|---|---|
| Material finer than ASTM # 200 Sieve | 0.32% |
| Loss on Abrasion | 23.5% |
| Clay lumps and friable particles | 0.45% |
| Mineralogical Composition | |
| $CaCO_3$ | 80% |
| $SiO_2$ | 20% |

#### 3.1.3.3 Crumb Rubber

Crumb rubber was obtained from Saudi Rubber Products Co., Second Industrial City, Dammam, Saudi Arabia. The physical properties of crumb rubber are shown in Table 3.6.

**Table 3-6: Physical properties of crumb rubber**

| Aggregate type | Specific gravity | Absorption (%) | Fineness Modulus | Unit weight ($kg/m^3$) |
|---|---|---|---|---|
| Rubber | 1.03 | 0.04 | 0.92 | - |

#### 3.1.3.4 Polypropylene

Polypropylene was obtained from Saudi Basic Industries Corporation (SABIC), Dammam, Saudi Arabia. The physical properties of polypropylene are shown in Table 3.7.

**Table 3-7: Physical properties of polypropylene**

| Aggregate type | Specific gravity | Absorption (%) | Fineness Modulus | Unit weight ($kg/m^3$) |
|---|---|---|---|---|
| Polypropylene | 0.886 | 0.008 | - | - |

#### 3.1.3.5 Scoria

Scoria was obtained from a quarry in the Western Province of Saudi Arabia. The physical properties of scoria are shown in Table 3.8.

**Table 3-8: Physical properties of scoria**

| Aggregate type | Specific gravity | Absorption (%) | Fineness Modulus | Unit weight ($kg/m^3$) |
|---|---|---|---|---|
| Scoria | 1.5 | 22.2 | 5.4 | 866 |

### 3.1.4 Super-plasticizer

Varying dosage (mostly 1.2% by weight of cement) of superplasticizer (SP 430) was used to obtain a slump of 100 ± 25 mm for all the mixes.

## 3.2 Mix Proportions

Several trial mixtures were prepared prior to the selection of detailed mixtures to understand the working of various constituents of LWC. Since LWC was proposed to be developed using materials which are not commonly used in the construction industry, there was a need to optimize some constituents of the concrete. Compressive strength and unit weight were the criteria for selecting the mixtures for detailed experimental program. Samples having higher compressive strength and unit weight on the lower side were selected. The details of the trial mixtures are shown in Table 3.9. The abbreviations used in the following tables are:

CA: coarse aggregate; FA: fine aggregate; TA: total aggregate; w/c: water cement ratio; OA: oil ash; PP: polypropylene; LS: limestone; CR: crumb rubber;

### Table 3-9: Details of 25 Trial Mixtures

| Mix # | Description of mix | Ingredients | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Cement kg/m$^3$ | CA type | FA type | CA/TA | FA/TA | OA /TA | w/c |
| 1 | Scoria as CA | 400 | Scoria | Sand | 0.45 | 0.55 | 0 | 0.4 |
| 2 | Scoria as CA | 400 | Scoria | Sand | 0.5 | 0.5 | 0 | 0.4 |
| 3 | Scoria as CA | 370 | Scoria | Sand | 0.45 | 0.55 | 0 | 0.4 |
| 4 | Scoria as CA and 10% OA replacing sand | 370 | Scoria | Sand + OA | 0.5 | 0.45 | 0.05 | 0.45 |
| 5 | PP as CA | 370 | PP | Sand | 0.5 | 0.5 | 0 | 0.45 |
| 6 | PP as CA with 10% OA replacing sand | 370 | PP | Sand + OA | 0.5 | 0.45 | 0.05 | 0.45 |
| 7 | CR as CA | 370 | CR | Sand | 0.5 | 0.5 | 0 | 0.45 |
| 8 | CR as CA with 10% OA replacing sand | 370 | CR | Sand + OA | 0.5 | 0.45 | 0.05 | 0.45 |
| 9 | LS as CA and 50% CR (0.25) as replacement of Sand | 370 | LS | Sand + CR | 0.5 | 0.25 | 0.25 (CR) | 0.45 |
| 10 | LS and 50% CR (0.25) as CA and 10% OA replacing sand | 370 | LS + CR | Sand + OA | 0.25 (LS) + 0.25 (CR) | 0.45 | 0.05 | 0.45 |
| 11 | 50% Scoria and 50% PP as CA | 370 | Scoria + PP | Sand | 0.25 (Scoria) + 0.25 (PP) | 0.5 | 0 | 0.45 |
| 12 | 50% LS and 50% PP as CA | 370 | LS + PP | Sand | 0.25 (LS) + 0.25 (PP) | 0.5 | 0 | 0.45 |
| 13 | Scoria as CA and 10% addition of CR (2.5mm ) replacing sand | 370 | Scoria | Sand + CR | 0.5 | 0.4 | 0.1 (CR) | 0.45 |
| 14 | Scoria as CA and 20% addition of CR | 370 | Scoria | Sand + CR | 0.5 | 0.3 | 0.2 (CR) | 0.45 |

| Mix # | Description of mix | Ingredients | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Cement kg/m$^3$ | CA type | FA type | CA/TA | FA/TA | OA /TA | w/c |
| 15 | Scoria as CA and 30% addition of CR (2.5mm ) replacing sand | 370 | Scoria | Sand + CR | 0.5 | 0.2 | 0.3 (CR) | 0.45 |
| 16 | LS as CA and 30% addition of CR (2.5mm ) replacing sand | 370 | LS | Sand + CR | 0.5 | 0.2 | 0.3 (CR) | 0.45 |
| 17 | LS as CA and 20% addition of CR (2.5mm ) replacing sand | 370 | LS | Sand + CR | 0.5 | 0.3 | 0.2 (CR) | 0.45 |
| 18 | LS as CA and 10% addition of CR (2.5mm ) replacing sand | 370 | LS | Sand + CR | 0.5 | 0.4 | 0.1 (CR) | 0.45 |
| 19 | LS (50%) as CA and 25% addition of OA replacing sand | 370 | LS | Sand + OA | 0.5 | 0.25 | 0.25 (OA) | 0.45 |
| 20 | LS as CA and 15% addition of CR (2.5mm ) replacing sand | 370 | LS | Sand + CR | 0.5 | 0.35 | 0.15 (CR) | 0.45 |
| 21 | LS as CA and 50% addition of PP replacing sand | 370 | LS | Sand + PP | 0.5 | 0.25 | 0.25 (PP) | 0.4 |
| 22 | Scoria as CA and 50% addition of PP replacing sand | 370 | Scoria | Sand | 0.5 | 0.25 | 0.25 (PP) | 0.4 |
| 23 | Scoria as CA and Sand (0.45) and CR (0.05) as FA replacing sand | 370 | Scoria | Sand | 0.5 | 0.45 | 0.05 (CR) | 0.4 |
| 24 | LS as CA and Sand (0.45) and CR (0.05) as FA replacing sand | 370 | LS | Sand | 0.5 | 0.45 | 0.05 (CR) | 0.4 |

After comparing the 7 days average compressive strength and unit weight of specimens prepared from the trial mixtures, 10 concrete mixtures resulting in 270 specimens were cast for detailed evaluation. All the mixtures had a constant water to cement ratio of 0.4. The details of the various proportions of concrete mixtures are as follows:

**Table 3-10: Details of 10 selected mixtures**

| Mix # | Description of Mix | Ingredients | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Cement kg/m$^3$ | CA type | FA type | CA/TA | FA/TA | | w/c |
| | | | | | | Sand | Additive | |
| 1 | Scoria as CA | 400 | Scoria | Sand | 0.5 | 0.5 | 0 | 0.4 |
| 2 | Scoria as CA | 400 | Scoria | Sand | 0.45 | 0.55 | 0 | 0.4 |
| 3 | Scoria as CA | 370 | Scoria | Sand | 0.45 | 0.55 | 0 | 0.4 |
| 4 | Scoria as CA and 10% OA replacing sand | 370 | Scoria | Sand + OA | 0.5 | 0.45 | 0.05 (OA) | 0.4 |
| 5 | PP as CA | 370 | PP | Sand | 0.5 | 0.5 | 0 | 0.4 |
| 6 | PP as CA with 10% OA replacing sand | 370 | PP | Sand + OA | 0.5 | 0.45 | 0.05 (OA) | 0.4 |
| 7 | 50% Scoria and 50% PP as CA | 370 | Scoria + PP | Sand | 0.25 Scoria + 0.25 PP | 0.5 | 0 | 0.4 |
| 8 | 50% LS and 50% PP as CA | 370 | LS + PP | Sand | 0.25 LS + 0.25 PP | 0.5 | 0 | 0.4 |
| 9 | Scoria as CA and 10% addition of CR (2.5mm) replacing sand | 370 | Scoria | Sand + CR | 0.5 | 0.45 | 0.05 (CR) | 0.4 |
| 10 | LS as CA and 10% addition of CR (2.5mm) replacing sand | 370 | LS (0.5) | Sand + (0.1) CR | 0.2 LS + 0.3 CR | 0.4 | 0.1 (CR) | 0.4 |

## 3.3 Preparation and Curing of Specimens

Concrete specimens were prepared and cured to carry out various tests planned in this study. Batching of each mix was proportioned by weight. Aggregates were initially sieved to obtain the required sizes. The concrete constituents were thoroughly mixed in an electrically operated mixer of 1.7 $m^3$ capacity till a uniform consistency was obtained. The mixed concrete was poured in the moulds of required shapes and sizes. The moulds were then vibrated until complete consolidation was achieved after a thin film of mortar appeared on the concrete surface. After casting, the specimens were covered with plastic sheet for 24 hours in the laboratory environment (22 ± 30 $^0$C) to minimize loss of mix water. After 24 hours, the specimens were demoulded and placed in a curing tank till the time of test. Table 3.9 shows the type and number of specimens used in this study.

**Table 3-11: Type and number of specimens prepared and tested.**

| No. | Tests | Specimen Type | Dimensions (mm) | Test Standard | Specimen Tested |
|---|---|---|---|---|---|
| 1 | Compressive strength | Cube | 100x100 | ASTM C 39 | 90 |
| 2 | Drying shrinkage | Prism | 25x25x275 | ASTM C 157 | 30 |
| 3 | Flexural strength | Prism | 40x40x160 | ASTM C 78 | 30 |
| 4 | Water absorption | Cylinder | 75x150 | ASTM C 642 | 30 |
| 5 | Thermal conductivity | Slab | 350x350x50 | ASTM C 201 | 10 |
| 6 | Chloride permeability | Cylinder | 100x200 | ASTM C 1202 | 20 |
| 7 | Corrosion potentials | Cylinder | 75x150 | ASTM C 876 | 30 |
| 8 | Corrosion current density | Cylinder | 75x150 | LPRM | |
| 9 | Modulus of elasticity | Cylinder | 75x150 | ASTM C 469 | 30 |
| | | | | Total Number of Specimens | 270 |

## 3.4 Testing

The following tests were conducted on the prepared specimens.

### 3.4.1 Compressive Strength

Compressive strength specimens were 100 mm × 100 mm × 100 mm concrete cubes. The compressive strength was determined according to ASTM C 39 [69] after 7, 14 and 28 days of water curing. The specimens were tested using an automatic compression machine of hydraulic type, shown in Figure 3.1. The compressive load was applied at a constant rate of 1.5 kN/s until the specimen failed. The maximum load (kN) was noted. The compressive strength was calculated by dividing the failure load by the cube cross-sectional area.


**Figure 3-1: Matest® hydraulic type compressive strength testing machine.**

### 3.4.2 Chloride Permeability

The chloride permeability of LWC specimens was assessed using rapid chloride permeability procedure of ASTM C1202 [70]. This method basically determines the electrical conductance of concrete in which the charge carrying species is chloride ion via the pores of the concrete.

A 50 mm thick concrete disk was cut out from the center of the 75 mm x 150 mm cylindrical specimen. The curved surfaces of the concrete disks were coated with epoxy, and then the disk specimens were conditioned in vacuum desiccator for 4 hrs. as described in ASTM

C1202. After conditioning, the disk specimens were left in water in the desiccators and kept saturated for about 18 hours.

Following the 18 hours of saturation, the disks were clamped between two half cells, one filled with 3% NaCl solution (w/w) and the other with 0.3N NaOH solution. An automatic computerized testing machine was used for the test. A potential difference of 60 V DC was maintained across each cell holding the specimens, and the current flowing through each one was recorded at intervals of 30 minutes by the computer, via the testing machine. The total charge passed, in Coulombs was recorded over a six hour period. The test was performed at a room temperature of 25°C. The machine handles all the relevant calculations contained in ASTM C1202 including correction for disk diameter. The final adjusted total charge was read and recorded from the computer. Figure 3.2 shows the test set-up.

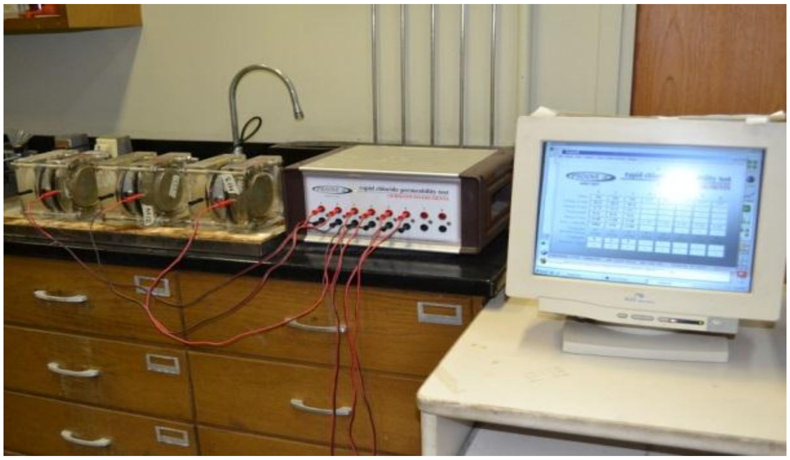

**Figure 3-2: Rapid chloride permeability test set-up.**

### 3.4.3 Corrosion Resistance

The corrosion resistance of LWC specimens was evaluated by exposing them to 5% sodium chloride solution. Reinforced LWC specimens, measuring 75 mm in diameter and 150 mm high, were prepared with a 12 mm diameter steel bar placed at the center. A cover of 25 mm was provided at the bottom. The reinforcing steel bars were coated with cement paste followed by an epoxy coating at the bottom of the bar and at the concrete-air interface to avoid crevice corrosion. Figure 3.3 shows the schematic view of the reinforced LWC specimen.

Reinforcement corrosion was monitored by measuring corrosion potentials, according to ASTM C876 [71], and the corrosion current density by the linear polarization resistance method (LRPM) [72]. The corrosion measurements were conducted at regular intervals.

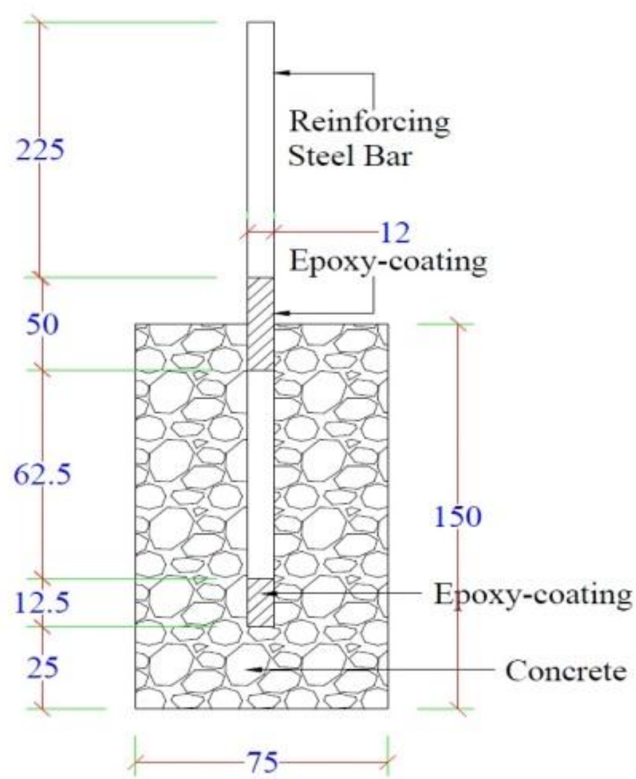


**Figure 3-3: Schematic diagram of corrosion resistance test specimen (Dimensions in mm).**

#### 3.4.3.1 Corrosion potentials

The corrosion potentials were measured using a saturated calomel reference electrode (SCE). The electrical lead from the reference electrode was connected to the positive terminal of a high impedance digital voltmeter while the steel bar in the concrete specimen was connected to its negative terminal. Figure 3.4 shows a set of specimen for corrosion measurements.


**Figure 3-4: Set of specimens used for corrosion measurement.**

#### 3.4.3.2 Corrosion current density

The three electrode method was utilized to measure the resistance to polarization ($R_p$) using a Potentiostat/Galvanostat. The steel rod was connected to the working electrode terminal while a steel plate and a reference electrode were connected to the counter and reference electrode terminals of the Potentiostat/Galvanostat, respectively. The setup is shown in Figure 3.5.

The steel was polarized to ± 10 mV of the corrosion potential at a rate of 3 mV/min and the resulting current between the counter and the working electrode was measured. Rp was determined as the slope of the current-potential curve. Corrosion current density ($I_{corr}$) was evaluated using the following relationship:

$$I_{\text{corr}} = \frac{B}{R_{\text{p}}}$$

where:

$I_{corr}$ = Corrosion current density, μA/cm$^2$

$R_p$ = Resistance to polarization, $\Delta E / \Delta I$, Ω.cm$^2$

$$B = \frac{\beta_a \, X \, \beta_c}{2.3(\beta_a + \beta_c)}$$

$\beta_a$ and $\beta_c$ are the anodic and cathodic Tafel constants, mV/decade, respectively.

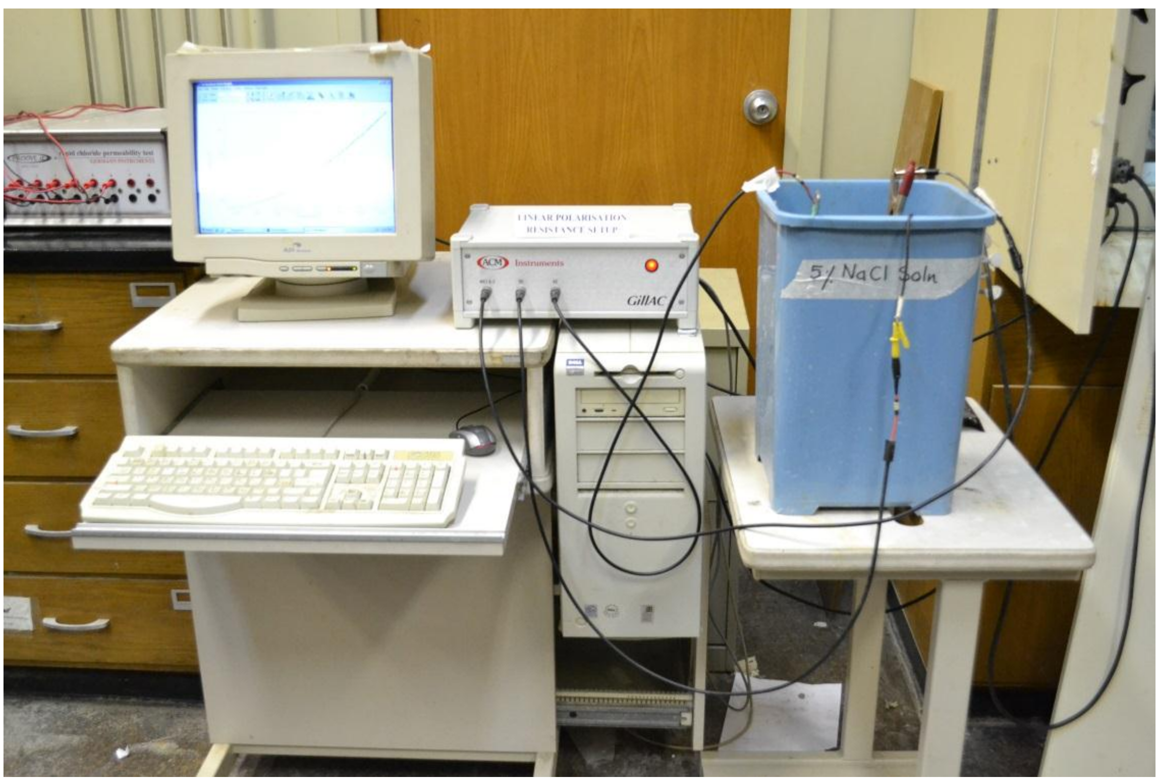


**Figure 3-5: Corrosion current density measurement setup.**

The Tafel constants are normally obtained by polarizing the steel to ± 250 mV of the corrosion potential (Tafel plot). However, in the absence of sufficient data on $\beta_a$ and $\beta_c$, a value of B equal to 26 mV for steel in active condition and 52 mV for steel in passive condition is often used [73]. Lambert et al [74] have reported a good correlation between corrosion rates determined using these values and the gravimetric weight loss method.

### 3.4.4 Water Absorption

Some voids will be left behind after the hydration process which affects the strength and durability of concrete. With the presence of air voids in concrete, it is vulnerable to penetration and attack by aggressive species (i.e., sulfates, chlorides, $CO_2$ etc.). Good quality concrete is characterized by having minimal voids left by excess water and, therefore, water absorption test is adopted for assessing the quality of concrete in terms of density, durability and imperviousness.

Water absorption was determined using 75 mm diameter and 150 mm high cylindrical concrete specimens according to ASTM C 642 [75], after 28 days of water curing. First, the specimens were dried in an oven for 24 hours at a temperature of 110 $^0$C and then their weights were recorded. They were then soaked in water for 48 hours and their saturated surface dry weights were taken. Water absorption was calculated utilizing the following formula.

Weight of saturated surface dried sample = A

Weight of oven dried sample = B

$$\text{Water Absorption} = \frac{A-B}{B} \times 100\%$$

Three specimens were tested and the average values were reported. The equipment used for determining the water absorption is shown in Figure 3.6.

(a) Specimens dried in oven


(b) Specimens immersed in water

**Figure 3-6: Equipment used to determine water absorption.**

### 3.4.5 Flexural Strength

The standard four-point flexural test to determine the modulus of rupture (MOR) according to ASTM C 78 [76], is the most common method for obtaining flexural strength of normal as well as high-performance concretes. The test setup is shown in Figure 3.7.


**Figure 3-7: Setup for conducting four-point bending test for MOR.**

This test involves the four-point flexural loading of small-scale concrete prisms measuring 40×40×160 mm (Figure 3.8). During the test, the load and the mid-span deflection of the prism are monitored. These data are then used to determine the MOR and flexural toughness. The residual flexural strength is also determined using the same load-deflection curve. This method uses similar test specimens and testing procedure as that of ASTM C 1609.

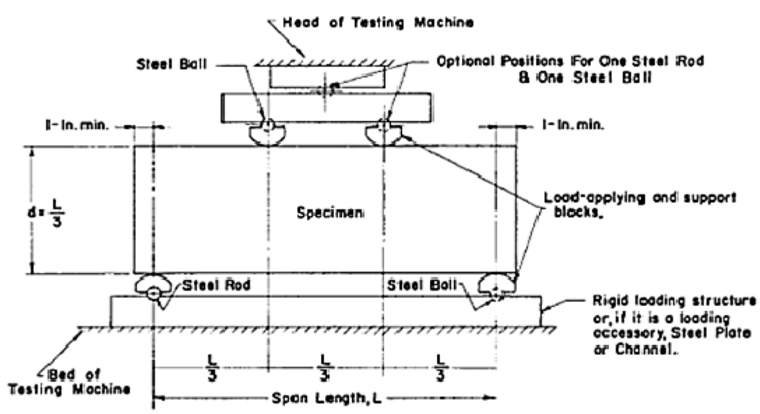


**Figure 3-8: Schematic of loading and measuring system for the four-point bending test.**

LWC prism specimens before and after failure are shown in Figure 3.9.

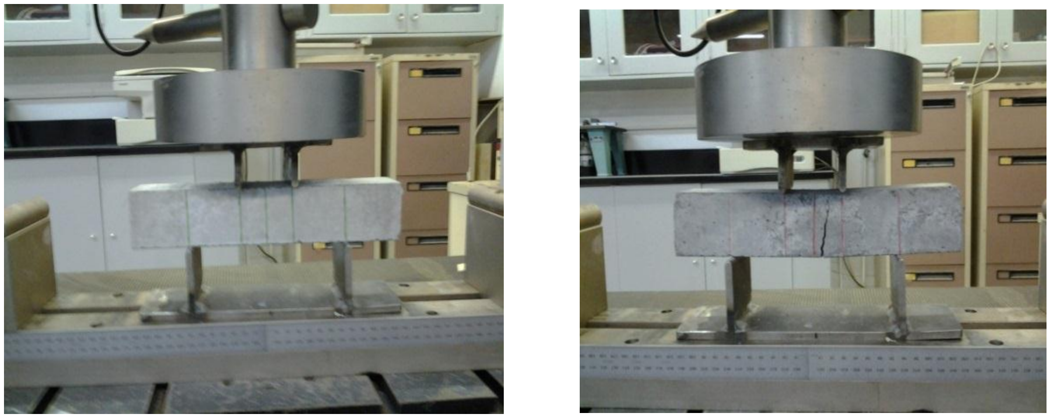

**Figure 3-9: Specimen before and after failure under four point bending test.**

### 3.4.6 Drying Shrinkage

Shrinkage is the reduction in the volume of concrete caused mainly by the loss of water due to evaporation from a freshly hardened concrete exposed to air. Shrinkage may result in cracking of restrained concrete members. A total of three LWC prism specimens of 25 x 25 x 275 mm were prepared for each mix for determining the drying shrinkage according to ASTM C 157 [77]. Three specimens were tested and their average values are reported. A setup consisting of a stand fitted with a LVDT connected to a data logger was used, as shown in Figure 3.10. Shrinkage measurements were taken after every seven days.

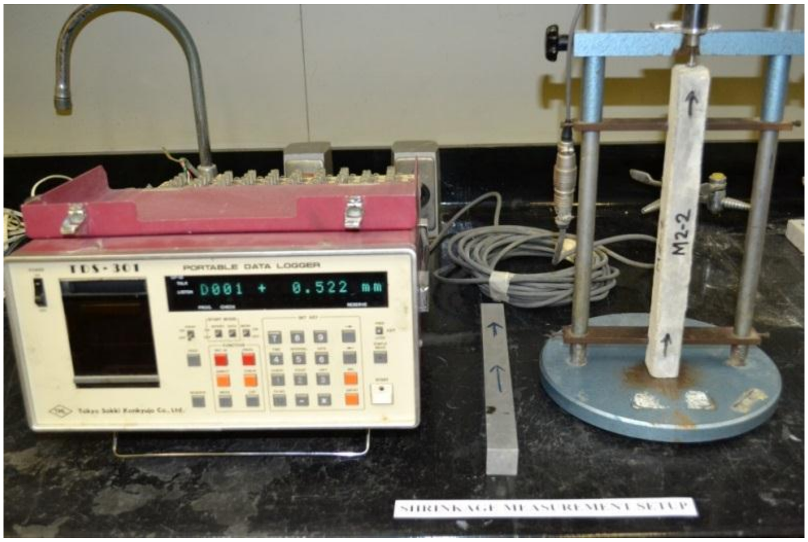


**Figure 3-10: Setup for measuring drying shrinkage.**

### 3.4.7 Thermal Conductivity

Thermal conductivity was measured under steady-state conditions using a guarded hot plate that conforms to ASTM Standard C 201 [78]. Slab specimens of dimensions 35 cm x 35 cm x 5 cm were prepared, as shown in Figure 3.11, to determine the thermal conductivity of each LWC mix.

**Figure 3-11: Slab specimens utilized for thermal conductivity measurements.**

The Dynatech guarded hot plate thermal conductance measuring system, TCFG-R4-6, shown in Figure 3.12, was used to determine the thermal conductivity of the developed LWC.

**Figure 3-12: Dynatech guarded hot plate thermal conductance measuring system.**

A schematic diagram of Dynatech guarded hot plate thermal conductance measuring system, TCFG-R4-6, is shown in Figure 3.13.

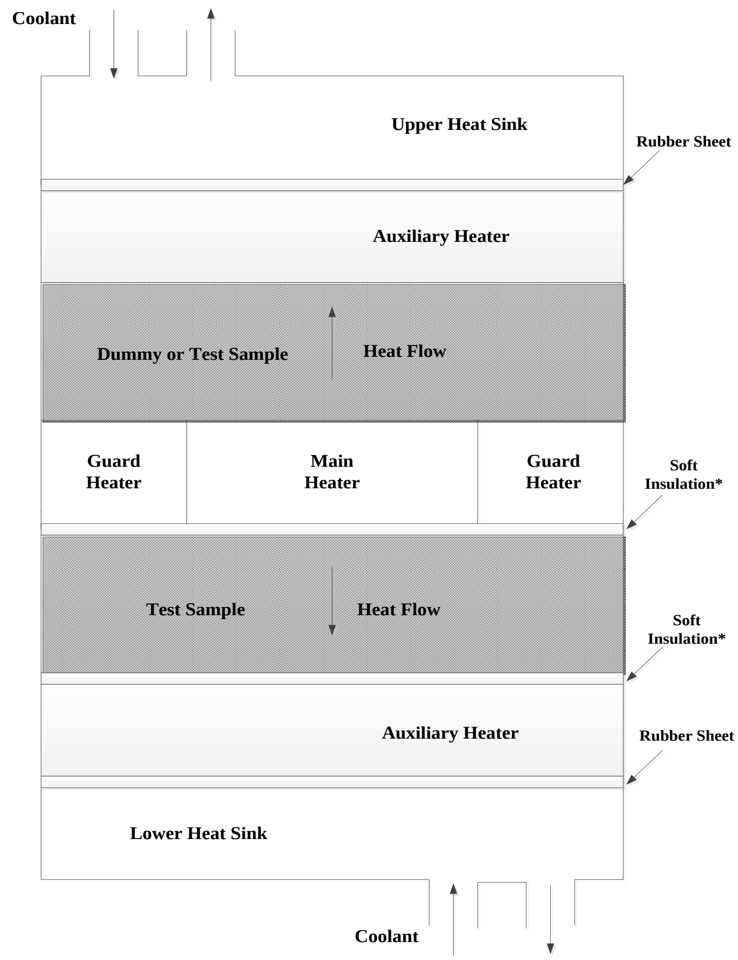


**Figure 3-13: Schematic Diagram of Dynatech guarded hot plate thermal conductance measuring system.**

The accuracy of the test equipment is about ± 4% of the true value of the thermal conductivity for samples with a maximum thickness of 15 cm. For samples of thickness of 15 to 20 cm, the accuracy of the test equipment is within 15% of the true value of the thermal conductivity. Tests were carried out under steady state conditions.

Since the setup requires a wall specimen of dimensions 61 cm x 61 cm and an even surface, the test specimen was fixed inside a thermacol sheet and wrapped inside a piece of soft, thick cloth as shown in Figure 3.14.

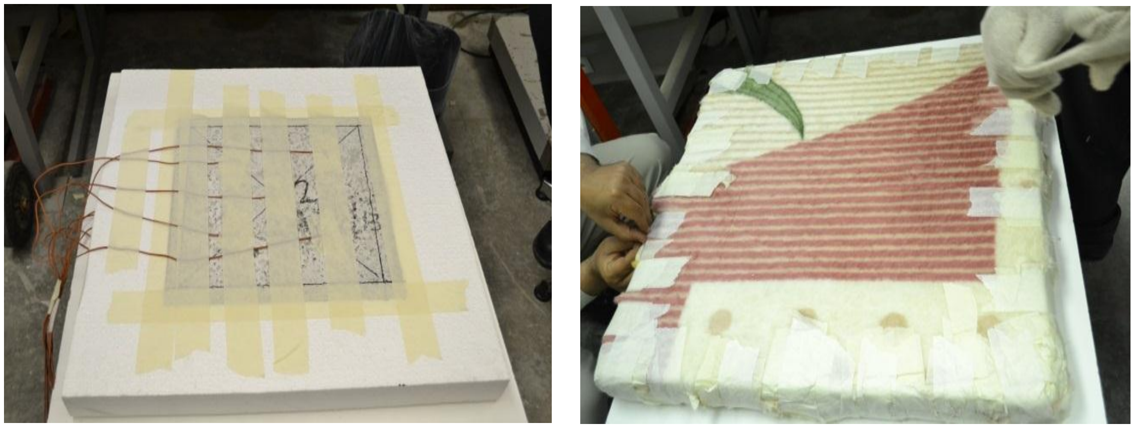

**Figure 3-14: Preparation of slab specimen for thermal conductivity test.**

During the tests, the average temperature of the specimens was about 35 ± 2 $^{0}$C with the cold surface maintained at about 25 $^{0}$C. These are realistic values for the outside and inside weather conditions in Saudi Arabia. Ten specimens, one from each mix, were tested. The whole thermal conductivity setup is shown in Figure 3.15.

**Figure 3-15: Thermal conductivity setup.**

### 3.4.8 Modulus of Elasticity

Three cylindrical specimens of dimensions 75 mm x 150 mm, were prepared from each mix for measuring the modulus of elasticity according to ASTM C 469 [79]. Since the test requires the top and bottom of the specimen to be smooth, sulfur capping was done to the top rough side of all the specimens. The curved surface of the cylindrical specimens was cleaned and two strain gauges were attached on opposite sides of the surface, by avoiding surface pores, as shown in Figure 3.16.

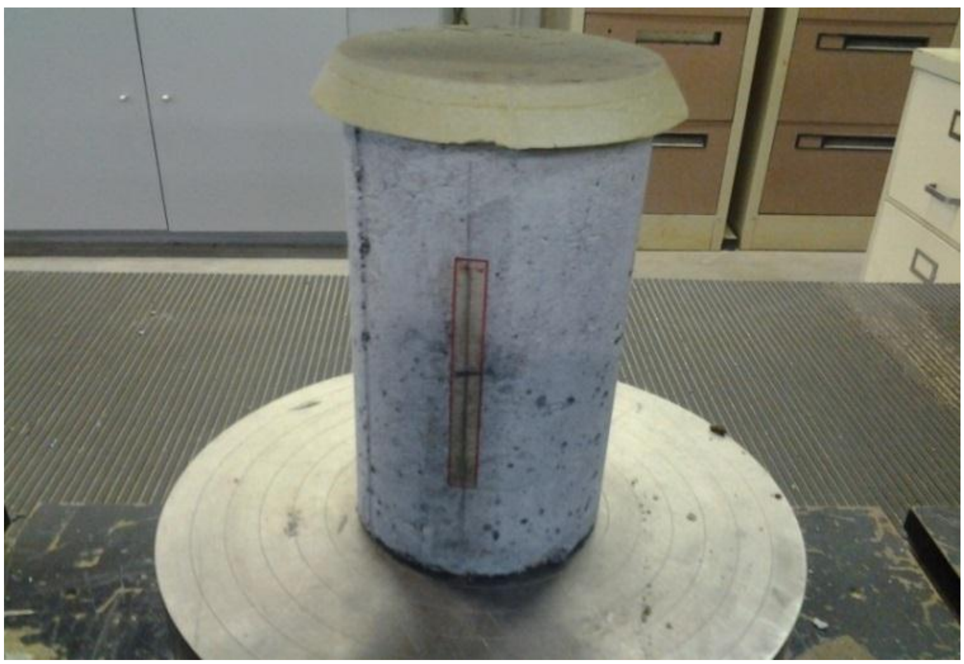

**Figure 3-16: Test specimen utilized to determine the modulus of elasticity.**

The test was performed on the Universal Testing Machine, Lloyd LR 300K. The strain gauge of the specimen was connected to a data logger and the specimen was loaded at a constant rate. Load was recorded for a constant rate of deformation values. The test setup is shown in Figure 3.17.


**Figure 3-17: Test setup for Modulus of elasticity.**

Data was recorded till the test sample failed under compression. Load per unit area gives the stress and deformation per unit length as recorded by the data logger through the strain gauge, gives the strain. Gauge factor of the strain gauge needs to be used in the calculation for obtaining the Modulus of Elasticity of the concrete. Specimens after failure are shown in Figure 3.18.

**Figure 3-18: Specimens after failure in compression.**

# CHAPTER 4

# RESULTS AND DISCUSSION

In this chapter, the results of the experimental work for concrete produced using lightweight materials (Scoria, Polypropylene, Oilash, and Rubber) are presented.

## 4.1 Unit Weight

The average 28 days unit weight of the specimen prepared for detailed evaluation are listed in Table 4.1 and depicted in Figure 4.1.

**Table 4-1: 28 days average unit weight of mixtures M1 to M10**

| Mix# | Description of mix | Average unit weight, kg/m$^3$ |
|---|---|---|
| M1 | Scoria as coarse aggregate | 1894 |
| M2 | Scoria as coarse aggregate | 1875 |
| M3 | Scoria as coarse aggregate | 1793 |
| M4 | Scoria as coarse aggregate and 10% oil ash replacing sand | 1891 |
| M5 | Polypropylene as coarse aggregate | 1421 |
| M6 | Polypropylene as coarse aggregate with 10% oil ash replacing sand | 1366 |
| M7 | 50% Scoria and 50% Polypropylene as coarse aggregate | 1621 |
| M8 | 50% Limestone and 50% Polypropylene as coarse aggregate | 1744 |
| M9 | Scoria as coarse aggregate and 10% rubber (2.5mm) replacing sand | 1809 |
| M10 | Limestone as coarse aggregate and 10% rubber (2.5mm) replacing sand | 2140 |

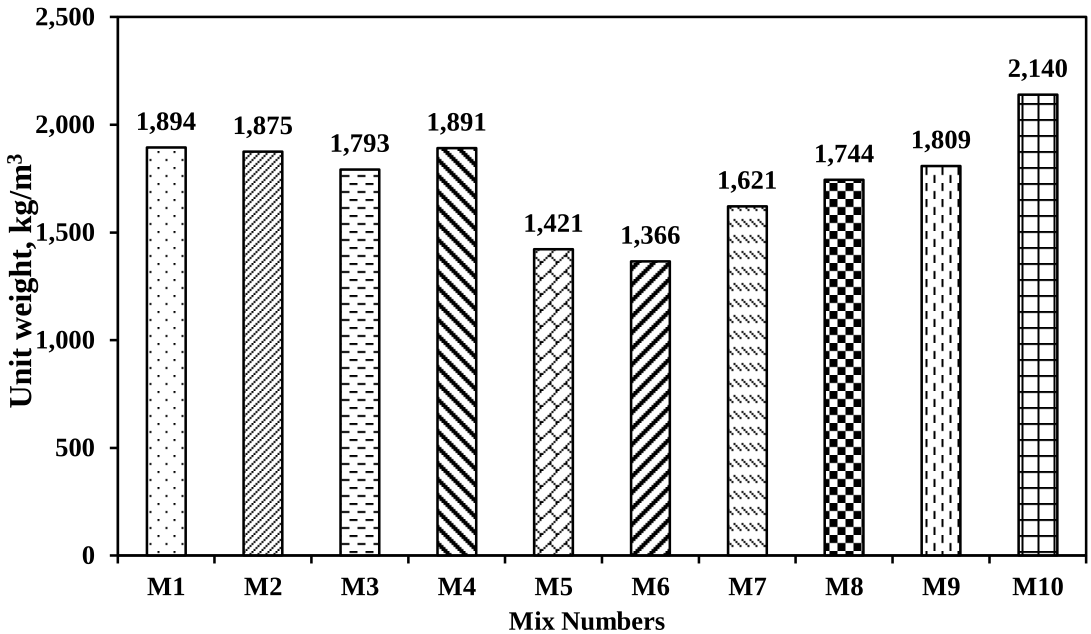


**Figure 4-1: Average 28 day unit weight of mixtures M1 to M10.**

The unit weight was in the range of 1366 to 2140 kg/m$^3$. The lowest unit weight was in the mixes with polypropylene (M5, M6, M7 and M8). The unit weight of mixtures with scoria (M1-M4) was in the range of 1793 to 1894 kg/m$^3$. The unit weight of mixtures containing polypropylene (M5-M8) was in the range of 1366 to 1744 kg/m$^3$. Highest unit weight of 2140 kg/m$^3$ was obtained for mix M10 containing rubber.

## 4.2 Compressive Strength Development

Structural LWC has a unit weight of the order of 1440 to 1840 kg/m$^3$ compared to NWC with unit weights in the range of 2240 to 2400 kg/m$^3$. For structural applications, the compressive strength should be more than 17.0 MPa.

According to ASTM standards, in order to produce structural lightweight concrete, the 28 day compressive strength requirements in the following table (Table 4.2) should be satisfied without exceeding the corresponding maximum density values.

**Table 4-2: Requirements of compressive strength for structural LWC**

| Calculated Equilibrium density max, kg/m$^3$ | Average 28-day compressive strength, min, MPa |
|---|---|
| 1840 | 28 |
| 1760 | 21 |
| 1680 | 17 |

### 4.2.1 28 days compressive strength variation with mixture variables

Mixtures are grouped for comparison based on the lightweight material present in them. Mixtures M1, M2 and M3 having only scoria as coarse aggregate, were grouped together. M4, M7 and M9 had scoria with another lightweight material as coarse aggregate. So, these mixtures are put in one group for comparison. Similarly, M5, M6, M7 and M8 containing polypropylene in their coarse content, will be compared. M9 and M10 have rubber as replacement of sand in the LWC mixtures.

#### 4.2.1.1 Scoria as coarse aggregate (M1, M2, M3)

The compressive strength variation of mixtures M1, M2 and M3 over 28 days is depicted in Figure 4.2 and their 28 days compressive strength is shown in Figure 4.3. The 28 days compressive strength of mix M2 with cement content of 400 kg/m$^3$ and, CA/TA and FA/TA of 0.5, was the highest among the three mixtures. Mixture M3 with a cement content of 370 kg/m$^3$ and, CA/TA and FA/TA of 0.45 and 0.55 respectively, exhibited the lowest compressive strength. The 28 days compressive strength of mixtures M1, M2 and M3 was 28.10, 29.54 and 25.56 MPa, respectively.

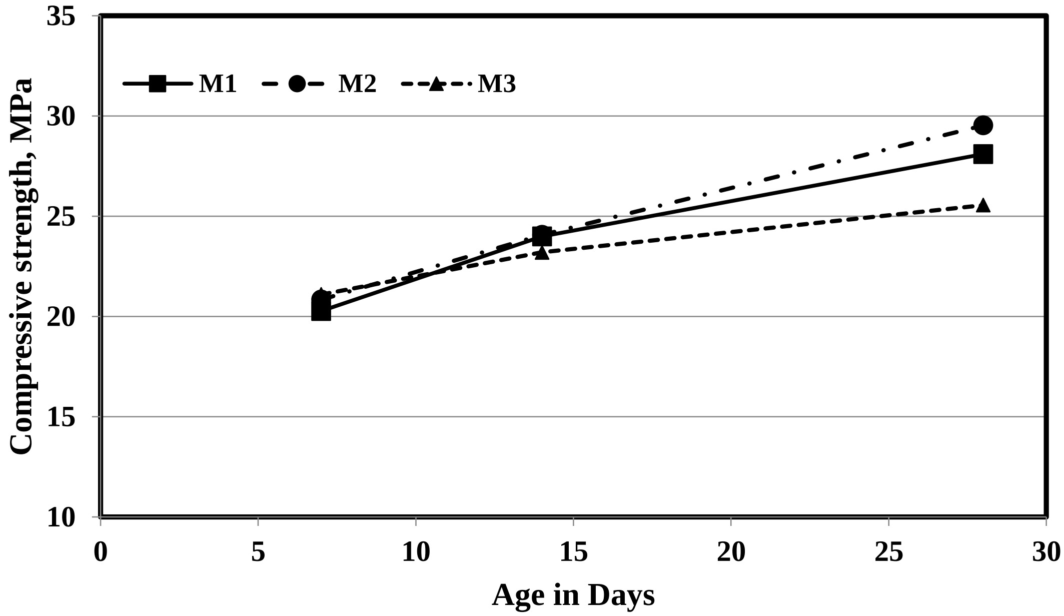


**Figure 4-2: Compressive strength variation of mixtures M1, M2 and M3**

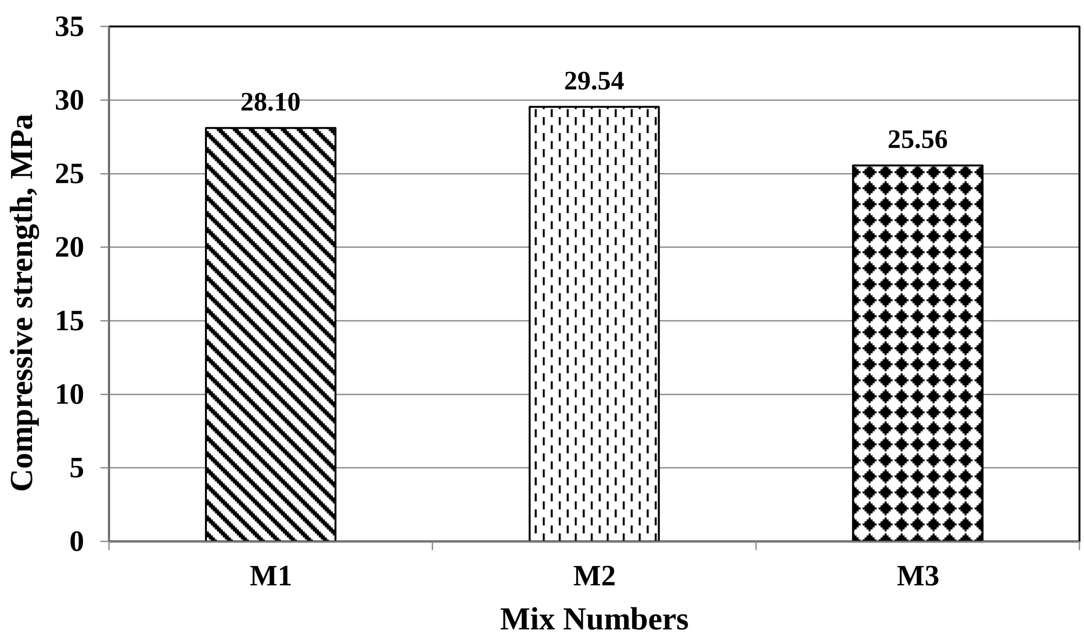


**Figure 4-3: 28 days compressive strength of mixtures M1, M2 and M3.**

#### 4.2.1.2 Scoria with lightweight material as coarse aggregate (M4, M7, M9)

The compressive strength variation of mixtures M4, M7 and M9 over 28 days is depicted in Figure 4.4 and their 28 days compressive strength is shown in Figure 4.5. Mix M7 exhibited a linear strength variation with age, whereas the strength development of mixtures M4 and M9 was higher for 7 to 14 days compared to 14 to 28 days. The 28 days compressive strength of mix M4 containing 10% oil ash as replacement of sand as fine aggregate was found to be the highest among the three mixtures. Mix M9 with 10% addition of rubber replacing sand as fine aggregate was found to possess the lowest compressive strength. The 28 days compressive strength of the three mixtures M4, M7 and M9 was found to be 23.68, 20.85 and 19.53 MPa, respectively.

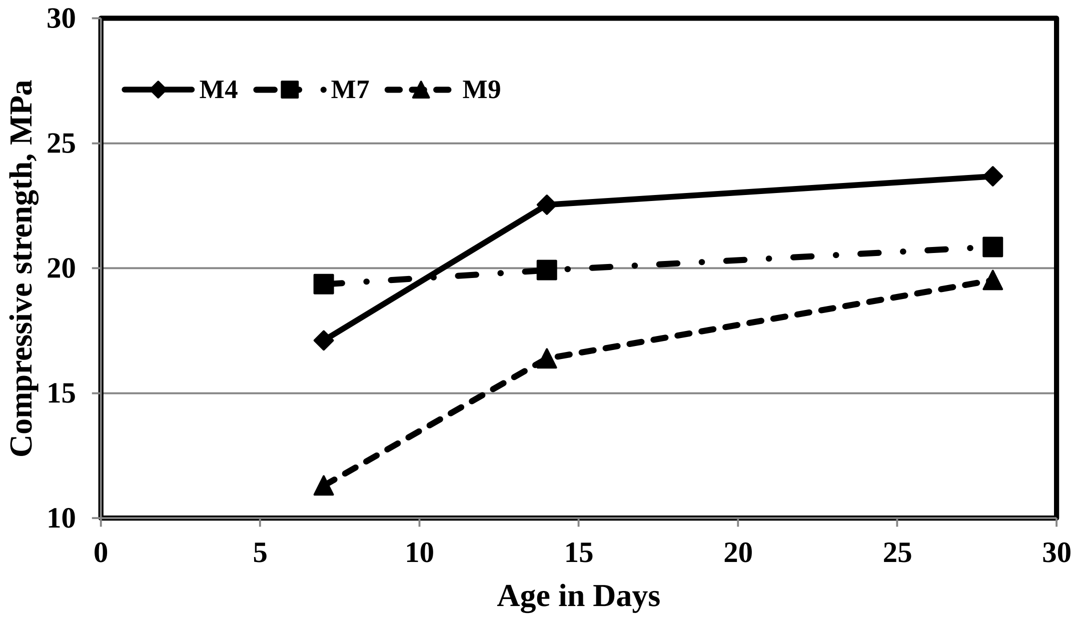


**Figure 4-4: Compressive strength variation of mixtures M4, M7 and M9**

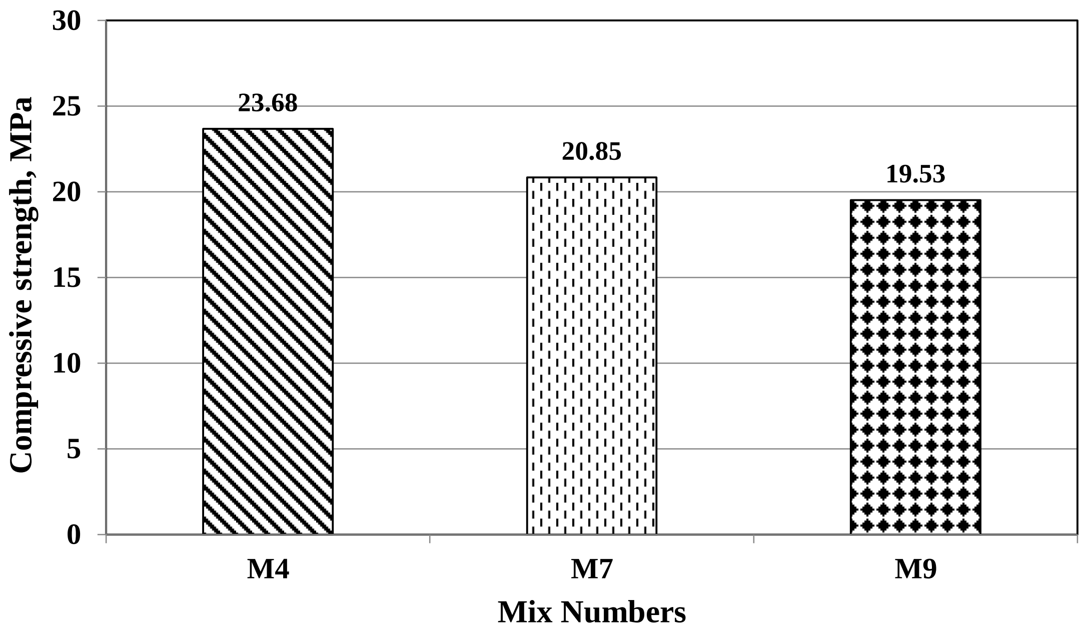


**Figure 4-5: 28 days compressive strength of mixtures M4, M7 and M9.**

#### 4.2.1.3 Polypropylene as coarse aggregate (M5, M6, M7, M8)

The compressive strength variation of mixtures M5, M6, M7 and M8 over 28 days is depicted in Figure 4.6 and their 28 days compressive strength is shown in Figure 4.7. The 28 days compressive strength of mix M8 containing polypropylene and limestone in equal proportions as coarse aggregate was the highest among the four mixtures. Mix M5 containing only polypropylene as coarse aggregate with CA/TA and FA/TA of 0.5 and 0.5, respectively exhibited the lowest compressive strength. The 28 days compressive strength of the four mixtures M5, M6, M7 and M8 was 16.93, 18.78, 20.85 and 26.53 MPa, respectively.

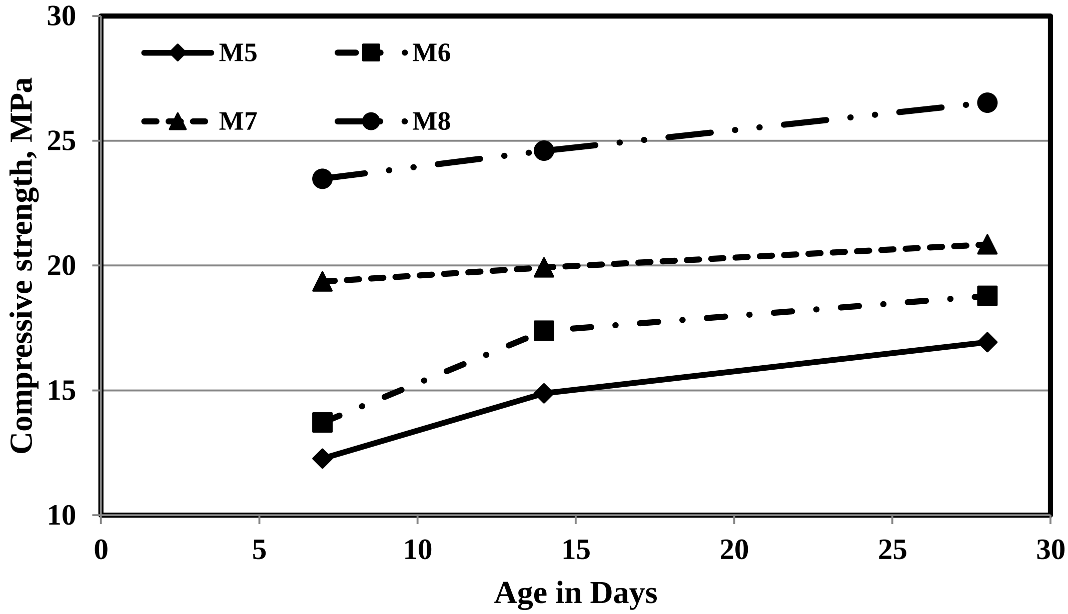


**Figure 4-6: Compressive strength variation of mixtures M5, M6, M7 and M8**

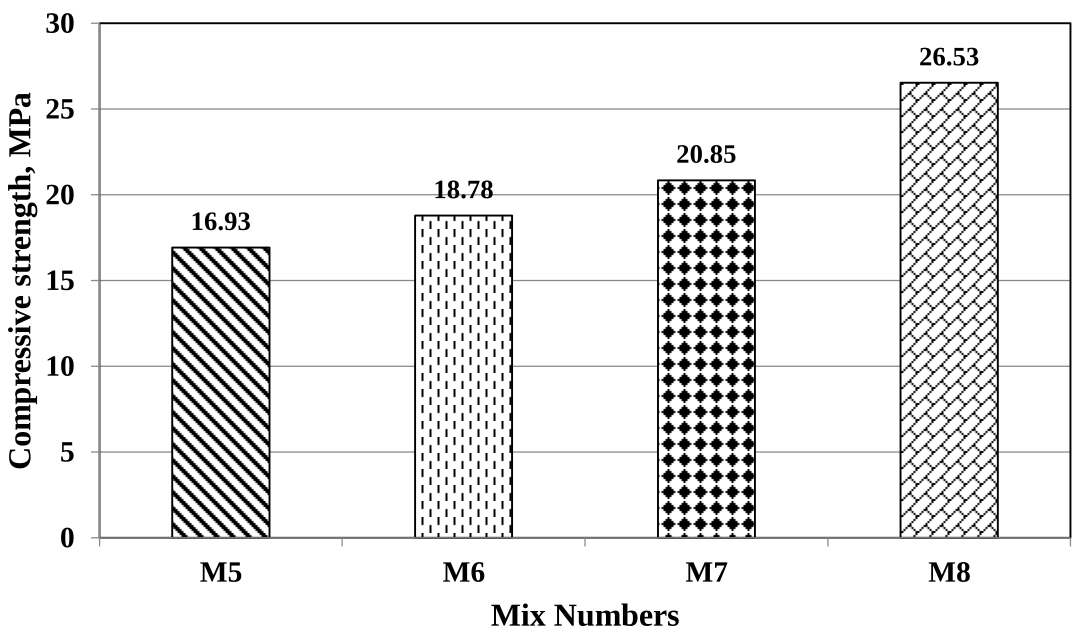


**Figure 4-7: 28 days compressive strength of mixtures M5, M6, M7 and M8.**

#### 4.2.1.4 Rubber as replacement of sand (M9, M10)

The compressive strength variation of mixtures M9 and M10 over 28 days is depicted in Figure 4.8 and their 28 days compressive strength is shown in Figure 4.9. The 28 days compressive strength of mix M10 containing limestone as coarse aggregate and 10% rubber as replacement of sand as fine aggregate was more than mix M9 containing scoria as coarse aggregate and 10% rubber as replacement of sand as fine aggregate. The 28 days compressive strength of the two mixtures M9 and M10 was 19.53 and 20.34 MPa, respectively.

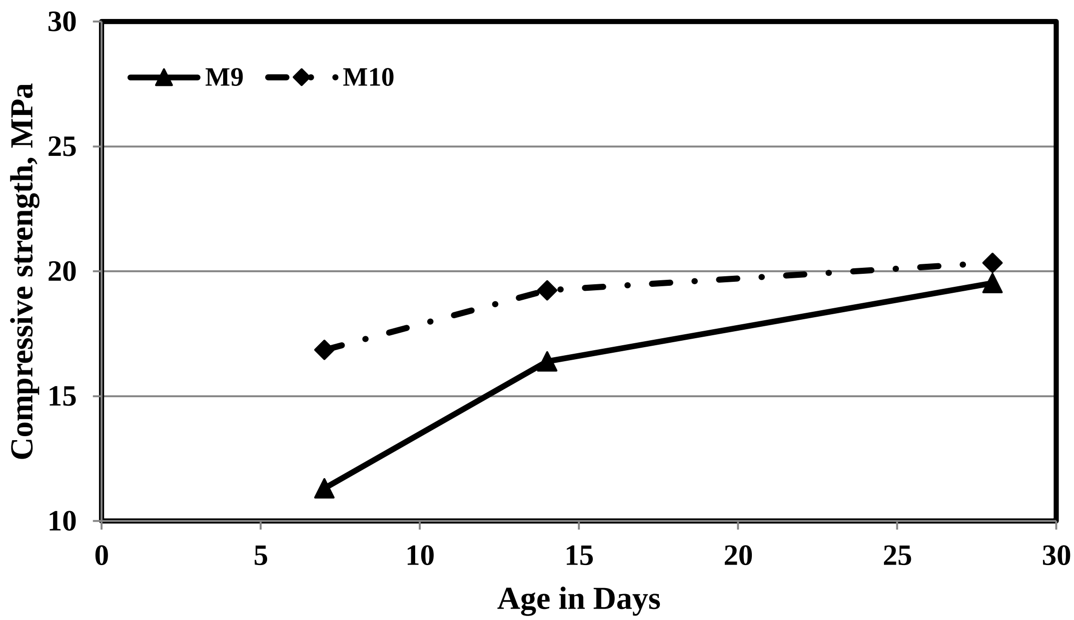


**Figure 4-8: Compressive strength variation of mixtures M9 and M10**

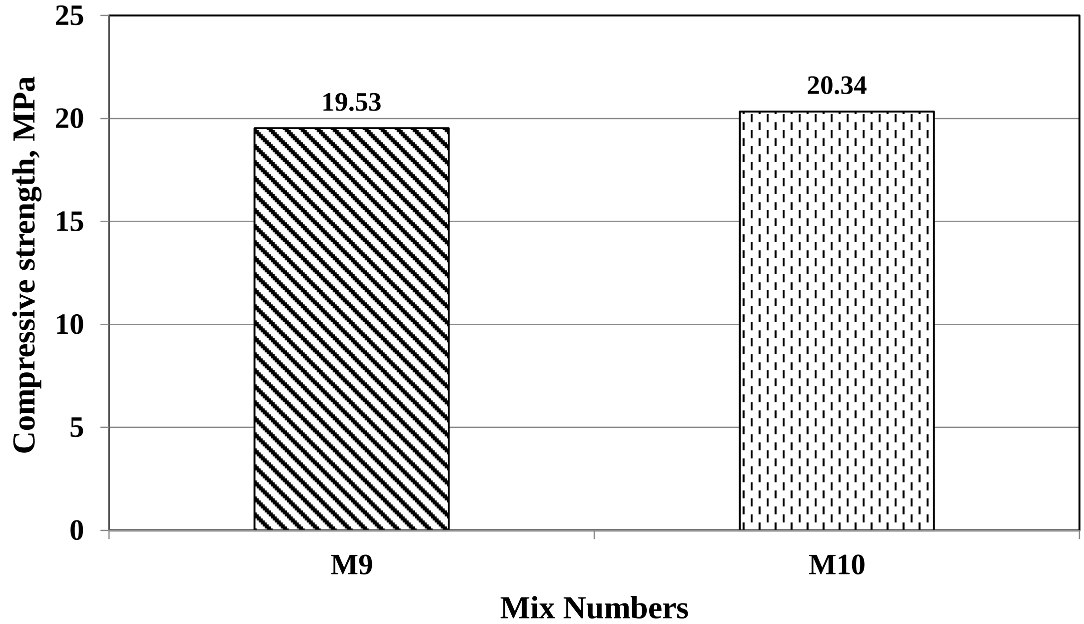


**Figure 4-9: 28 days compressive strength of mixtures M9 and M10.**

## 4.3 Flexural Strength

According to ASTM standards, in order to produce structural lightweight concrete, the 28 day splitting tensile strength requirements in the following table (Table 4.3) should be satisfied without exceeding the corresponding maximum density values.

**Table 4-3: Requirements for splitting tensile strength of LWC for structural purposes.**

| Calculated Equilibrium Density max, $kg/m^3$ | Average 28-day Splitting Tensile Strength, MPa |
|---|---|
| 1840 | 2.3 |
| 1760 | 2.1 |
| 1680 | 2.1 |

The 28 days average modulus of rupture (MOR) values obtained for the 50 x 50 x 250 mm prism specimens for all the ten mixtures are shown in Table 4.4.

**Table 4-4: 28 days average modulus of rupture.**

| Mix | Description | Modulus of Rupture, MPa | Max deflection, mm |
|---|---|---|---|
| M1 | Scoria as coarse aggregate | 5.30 | 0.9595 |
| M2 | Scoria as coarse aggregate | 4.66 | 0.6475 |
| M3 | Scoria as coarse aggregate | 4.71 | 0.7413 |
| M4 | Scoria as coarse aggregate and 10% Oilash replacing sand | 4.28 | 0.7087 |
| M5 | Polypropylene as coarse aggregate | 1.75 | 0.4627 |
| M6 | Polypropylene as coarse aggregate with 10% Oilash replacing sand | 1.82 | 0.6607 |
| M7 | 50% Scoria and 50% polypropylene as coarse aggregate | 2.37 | 0.5555 |
| M8 | 50% Limestone and 50% polypropylene as coarse aggregate | 2.74 | 0.6436 |
| M9 | Scoria as Coarse Aggregate and 10% addition of Rubber (2.5mm ) replacing sand | 3.21 | 0.7241 |
| M10 | Limestone as Coarse Aggregate and 10% addition of Rubber (2.5mm ) replacing sand | 2.81 | 0.5592 |

The MOR values of the developed LWC are discussed in detail by grouping the mixtures according to their constituents.

### 4.3.1 Scoria as coarse aggregate (M1, M2, M3)

The 28 days average MOR of mixtures M1, M2 and M3 is depicted for comparison in Figure 4.10. All the three mixtures possess high flexural strength. Among the three mixtures, the 28 days average MOR was highest for M1 and lowest for M2. Mixtures M2 and M3 had almost the same MOR values. The 28 days average MOR for M1, M2 and M3 was 5.3, 4.66 and 4.71 MPa, respectively.

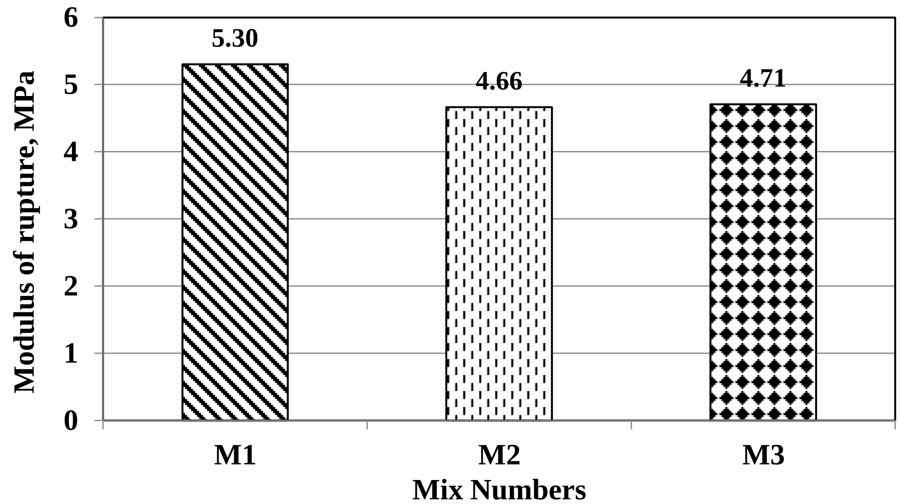


**Figure 4-10: 28 days average MOR for mixtures M1, M2 and M3.**

### 4.3.2 Scoria with lightweight material as coarse aggregate (M4, M7, M9)

The 28 days average MOR of mixtures M4, M7 and M9 is depicted for comparison in Figure 4.11. Among the three mixtures, the 28 days average MOR was highest for mix M4 containing scoria with 10% oil ash as replacement of sand and lowest for mix M7 containing equal amounts of scoria and polypropylene as coarse aggregate. The 28 days average MOR for mixtures M4, M7 and M9 was 4.28, 2.37 and 3.21 MPa, respectively.

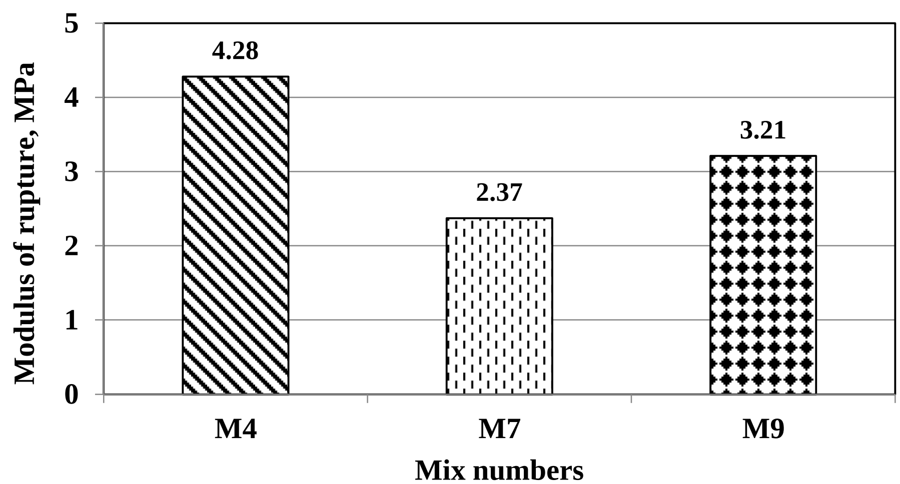


**Figure 4-11: 28 days average MOR for mixtures M4, M7 and M9.**

### 4.3.3 Polypropylene as coarse aggregate (M5, M6, M7, M8)

The 28 days average MOR of mixtures M5, M6, M7 and M8 is depicted for comparison in Figure 4.12. Among the four mixtures, the 28 days average MOR was the highest for mix M8 containing equal weights of polypropylene and limestone, and the lowest value for mix M5 containing only polypropylene as coarse aggregate. The average 28 days MOR values for mixtures M5 and M6 are almost the same. The 28 days average MOR for mixtures M5, M6, M7 and M8 was found to be 1.75, 1.82, 2.37 and 2.74 MPa, respectively.

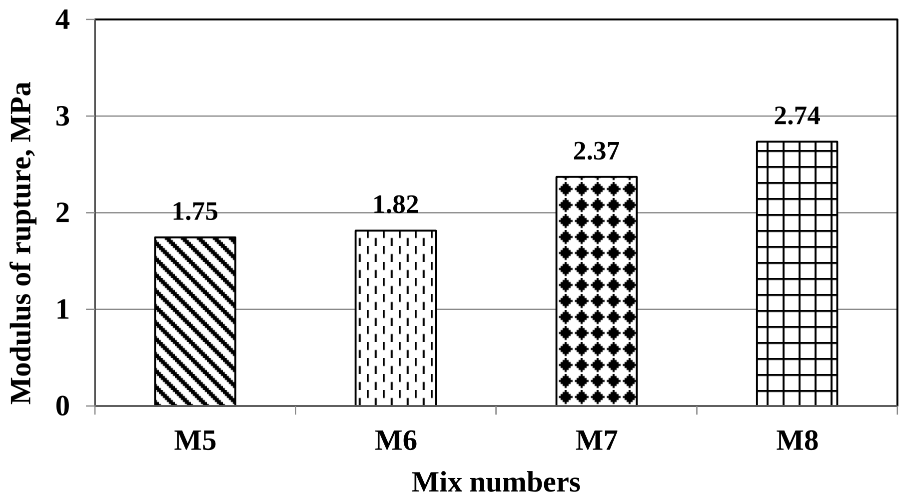


**Figure 4-12: 28 days average MOR for mixtures M5, M6, M7 and M8.**

### 4.3.4 Rubber as replacement of sand (M9, M10)

The 28 days average MOR of mixtures M9 and M10 is depicted for comparison in Figure 4.13. Among the two mixtures, the 28 days average MOR was the highest for mix M9 containing scoria as coarse aggregate and 10% rubber replacing sand as fine aggregate, and the lowest MOR for M10 containing limestone as coarse aggregate and 10% addition of rubber replacing sand as fine aggregate. The 28 days average MOR for mixtures M9 and M10 was 3.21 and 2.81 MPa, respectively.

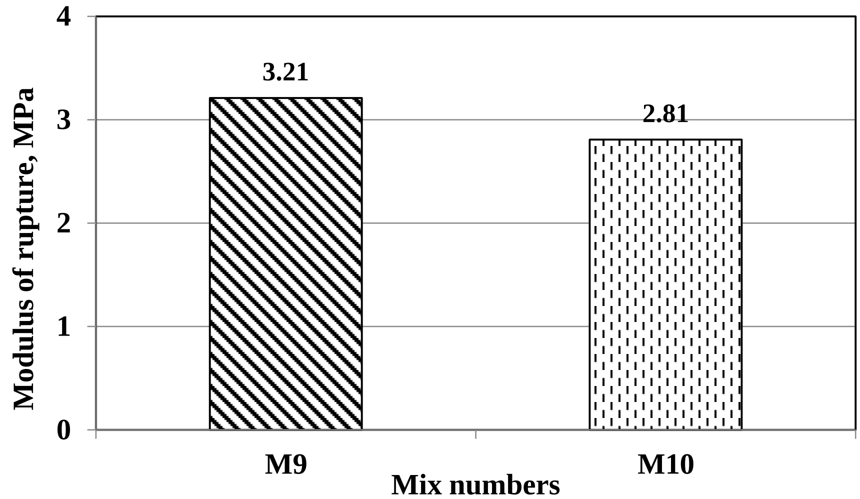


**Figure 4-13: 28 days average MOR for mixtures M9 and M10.**

## 4.4 Modulus of Elasticity

Table 4.5 list the average values of modulus of elasticity after water-curing the LWC specimens for 28 days.

**Table 4-5: Average 28 days modulus of elasticity of the developed LWC mixtures.**

| Mix | Description | Modulus of Elasticity, GPa |
|---|---|---|
| M1 | Scoria as coarse aggregate | 17.86 |
| M2 | Scoria as coarse aggregate | 17.77 |
| M3 | Scoria as coarse aggregate | 20.61 |
| M4 | Scoria as coarse aggregate and 10% oilash replacing sand | 16.38 |
| M5 | Polypropylene as coarse aggregate | 3.95 |
| M6 | Polypropylene as coarse aggregate with 10% oilash replacing sand | 4.09 |
| M7 | 50% Scoria and 50% polypropylene as coarse aggregate | 5.62 |
| M8 | 50% Limestone and 50% polypropylene as coarse aggregate | 7.50 |
| M9 | Scoria as Coarse Aggregate and 10% addition of Rubber (2.5mm ) replacing sand | 12.77 |
| M10 | Limestone as Coarse Aggregate and 10% addition of Rubber (2.5mm ) replacing sand | 14.66 |

### 4.4.1 Scoria as coarse aggregate (M1, M2, M3)

The 28 days average modulus of elasticity of mixtures M1, M2 and M3 is depicted for comparison in Figure 4.14. Among the three mixtures, the 28 days modulus of elasticity value was the highest for mix M3 and the lowest for mix M2. However, the modulus of elasticity of mixtures M1 and M2 was almost the same. The 28 days modulus of elasticity for mixes M1, M2 and M3 was 17.86, 17.77 and 20.61 GPa, respectively.

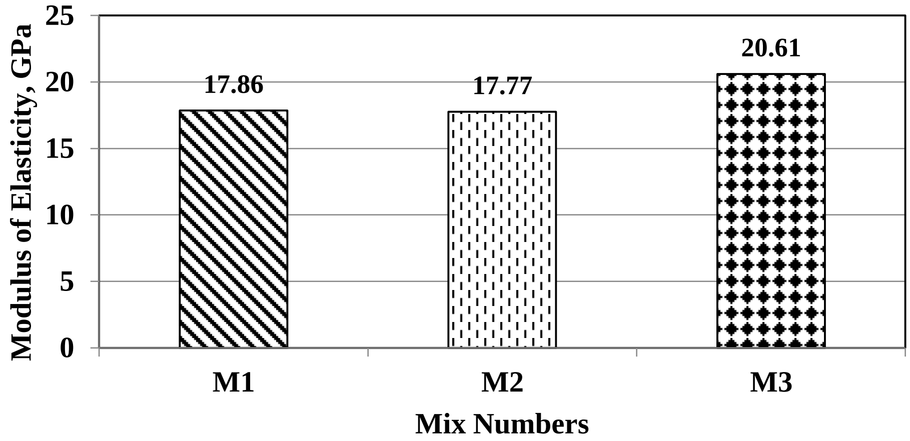


**Figure 4-14: 28-day modulus of elasticity of mixtures M1, M2 and M3.**

### 4.4.2 Scoria with lightweight material as coarse aggregate (M4, M7, M9)

The 28 days average modulus of elasticity of mixtures M4, M7 and M9 is depicted for comparison in Figure 4.15. Among the three mixtures, the 28 days modulus of elasticity value was the highest for mix M4 containing scoria as coarse aggregate and 10% oil ash replacing sand as fine aggregate and the lowest for mix M7 containing equal amounts of scoria and polypropylene as coarse aggregate. The 28 days modulus of elasticity for mixes M4, M7 and M9 were 16.38, 5.62 and 12.77 GPa, respectively.

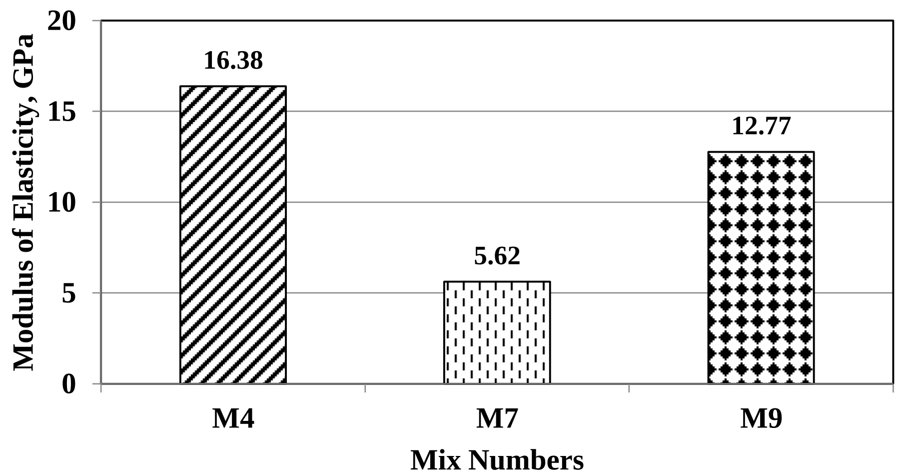


**Figure 4-15: 28-day modulus of elasticity of mixes M4, M7 and M9.**

### 4.4.3 Polypropylene as coarse aggregate (M5, M6, M7, M8)

The 28 days average modulus of elasticity of mixtures M5, M6, M7 and M8 is depicted for comparison in Figure 4.16. Among the four mixtures, the 28 days modulus of elasticity was the highest for mix M8 containing equal amounts of polypropylene and limestone as coarse aggregate and the lowest for mix M5 containing only polypropylene as coarse aggregate. The modulus of elasticity of M5 and M6 are almost similar. The 28 days modulus of elasticity for mixtures M5, M6, M7 and M8 was 3.95, 4.09, 5.62 and 7.5 GPa, respectively.

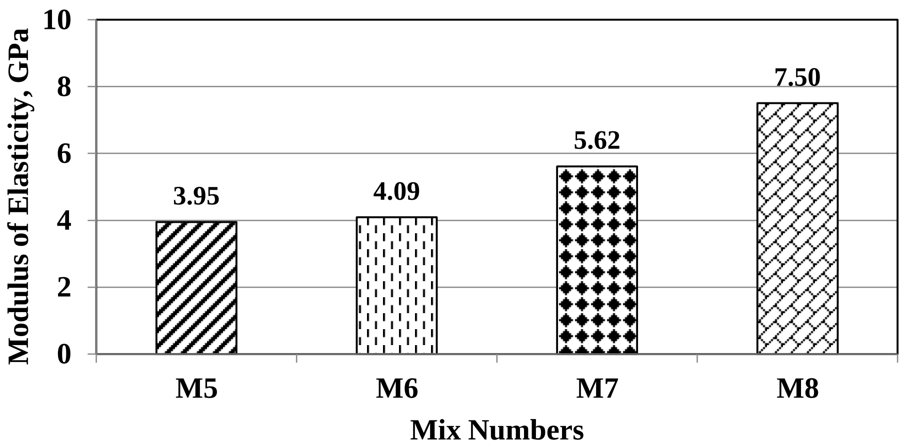


**Figure 4-16: 28-day modulus of elasticity of mixes M5, M6, M7 and M8.**

### 4.4.4 Rubber as replacement of sand (M9, M10)

The 28 days average modulus of elasticity for mixtures M4, M7 and M9 is depicted for comparison in Figure 4.17. Among the three mixtures, the 28 days modulus of elasticity value was the highest for mix M4 containing scoria as coarse aggregate and 10% oil ash replacing sand as fine aggregate and the lowest for mix M7 containing equal amounts of scoria and polypropylene as coarse aggregate. The 28 days modulus of elasticity for mixtures M4, M7 and M9 was 16.38, 5.62 and 12.77 GPa, respectively.

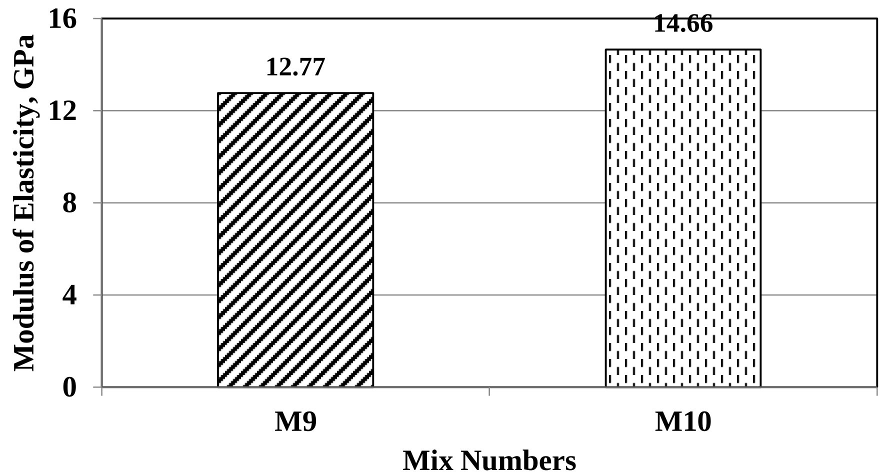


**Figure 4-17: 28 day modulus of elasticity of mixes M9 and M10.**

## 4.5 Thermal Conductivity

The thermal conductivity results obtained on 350 x 350 x 50 mm slab specimens of the developed LWC mixtures are shown in detail in Table 4.6.

**Table 4-6: Test results for thermal conductivity for all LWC mixtures.**

| Mix # | Dimensions (cm) | Test Thickness (cm) | Mean Temp (°C) | Thermal Conductivity (W/m.K) | Thermal Resistance ($m^2$.K/W) |
|---|---|---|---|---|---|
| M1 | 35 x 35 x 5 | 5.18 | 35.65 | 0.630 | 0.082 |
| M2 | 35 x 35 x 5 | 5.22 | 36.56 | 0.556 | 0.094 |
| M3 | 35 x 35 x 5 | 5.23 | 37.12 | 0.560 | 0.093 |
| M4 | 35 x 35 x 5 | 5.35 | 34.61 | 0.577 | 0.093 |
| M5 | 35 x 35 x 5 | 5.70 | 34.90 | 0.338 | 0.169 |
| M6 | 35 x 35 x 5 | 5.16 | 34.99 | 0.428 | 0.121 |
| M7 | 35 x 35 x 5 | 5.44 | 33.60 | 0.392 | 0.139 |
| M8 | 35 x 35 x 5 | 5.28 | 33.75 | 0.510 | 0.104 |
| M9 | 35 x 35 x 5 | 5.26 | 35.70 | 0.544 | 0.097 |
| M10 | 35 x 35 x 5 | 5.04 | 34.52 | 0.706 | 0.071 |

These thermal conductivity values are discussed in detail by grouping the mixtures according to the constituents of the LWC.

### 4.5.1 Scoria as coarse aggregate (M1, M2, M3)

The 28 days thermal conductivity values of mixtures M1, M2 and M3 is depicted for comparison in Figure 4.18. Among the three mixtures, the 28 days thermal conductivity value was the lowest in mix M2 and highest in mix M1. M3 and M2 had almost the same thermal conductivity values. The 28 days thermal conductivity values for mixtures M1, M2 and M3 was 0.63, 0.556 and 0.56 W/mK, respectively.

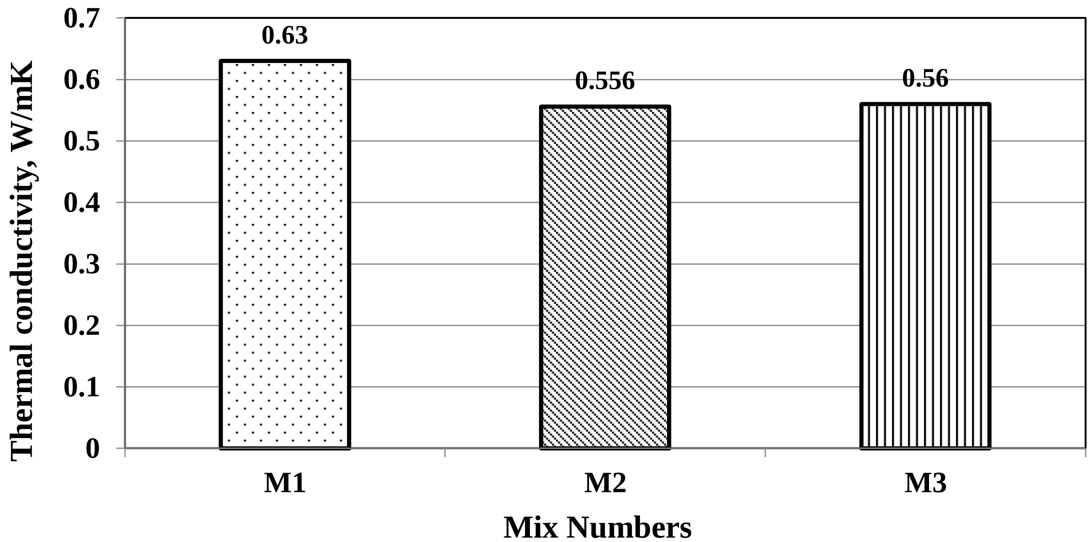


**Figure 4-18: 28 days thermal conductivity values for mixes M1, M2 and M3.**

### 4.5.2 Scoria with lightweight material as coarse aggregate (M4, M7, M9)

The 28 days thermal conductivity values of mixtures M4, M7 and M9 is depicted for comparison in Figure 4.19. Among the three mixtures, the 28 days thermal conductivity value was the lowest for mix M7 containing equal amounts of scoria and polypropylene as coarse aggregate and the highest for the mix M4 containing scoria with 10% oil ash as replacement of sand. The thermal conductivity value for mixes M4 and M9 was almost similar. The 28 days thermal conductivity value for mixtures M4, M7 and M9 was 0.577, 0.392 and 0.544 W/mK, respectively.

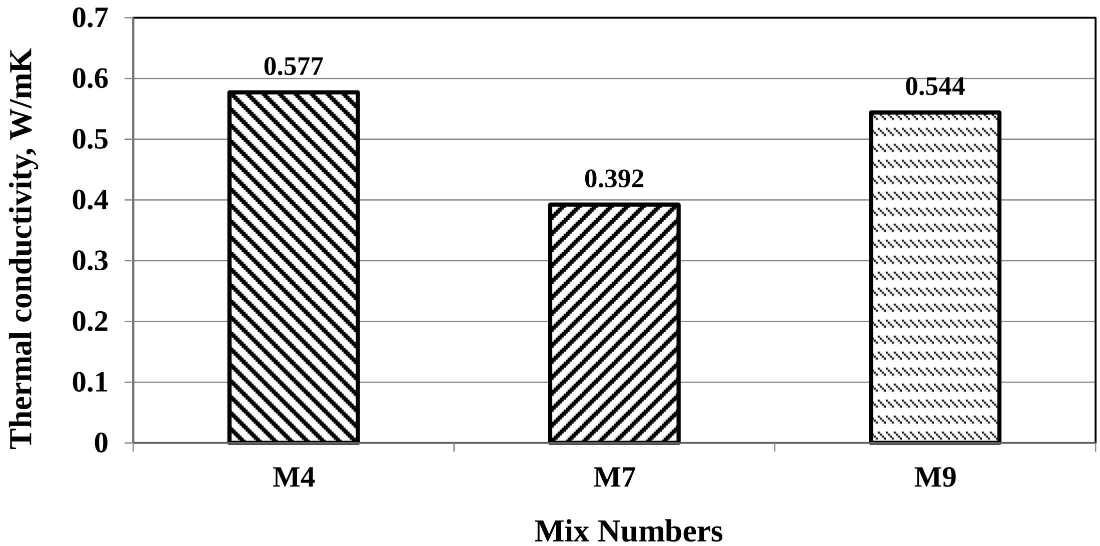


**Figure 4-19: 28 days thermal conductivity values for mixes M4, M7 and M9.**

### 4.5.3 Polypropylene as coarse aggregate (M5, M6, M7, M8)

The 28 days thermal conductivity values of mixtures M5, M6, M7 and M8 is depicted for comparison in Figure 4.20. Among the four mixtures, the 28 days thermal conductivity value was the lowest in mix M5 containing only polypropylene as coarse aggregate and the highest for mix M8 containing equal amounts of polypropylene and limestone. The 28 days thermal conductivity value for mixes M5, M6, M7 and M8 was 0.338, 0.428, 0.392 and 0.51 W/mK, respectively.

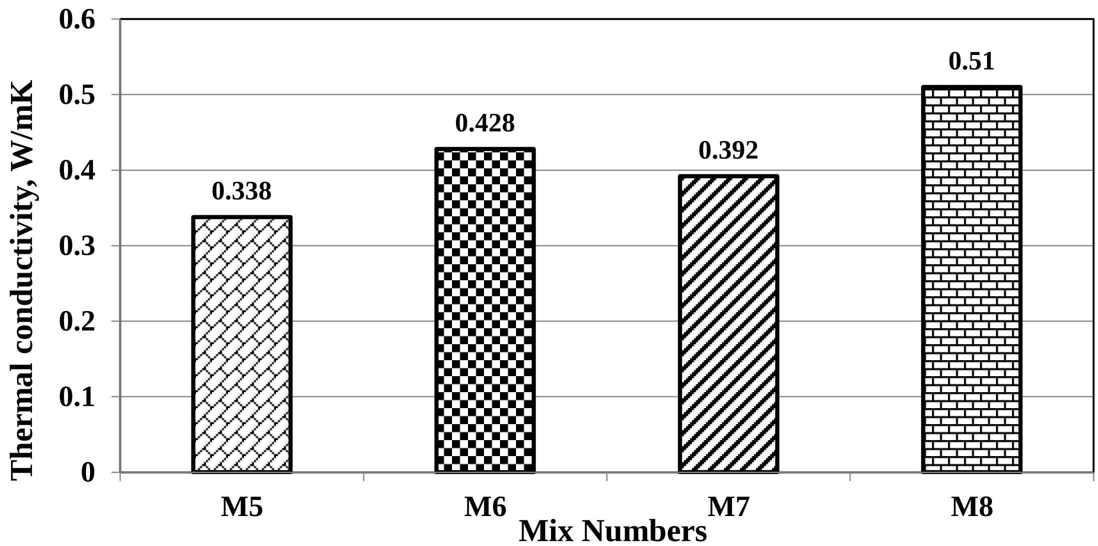


**Figure 4-20: 28 days thermal conductivity values for mixes M5, M6, M7 and M8.**

### 4.5.4 Rubber as replacement of sand (M9, M10)

The 28 days thermal conductivity values of mixtures M9 and M10 is depicted for comparison in Figure 4.21. Among the two mixtures, the 28 days thermal conductivity value was the lowest for mix M9 containing scoria as coarse aggregate and 10% rubber replacing sand, as fine aggregate, and highest for mix M10 containing limestone as coarse aggregate and 10% addition of rubber replacing sand as fine aggregate. The 28 days thermal conductivity value for mixtures M9 and M10 was 0.544 and 0.706 W/mK, respectively.

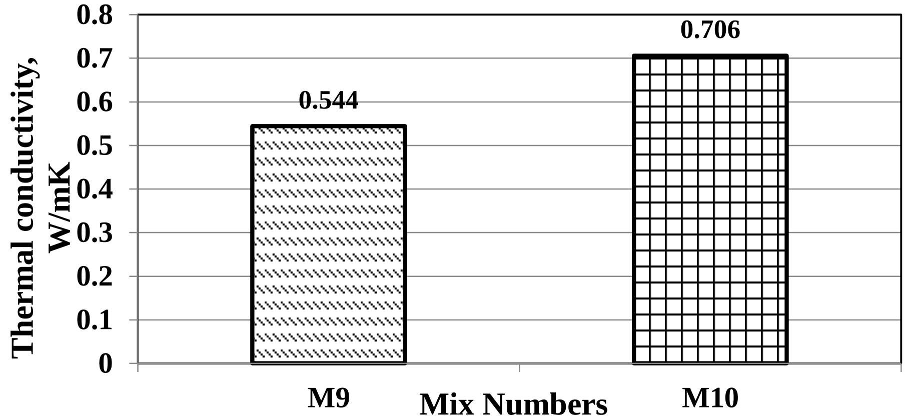


**Figure 4-21: 28 day thermal conductivity values for mixes M9 and M10.**

## 4.6 Water Absorption

Table 4.7 lists the average values of water absorption for all the LWC mixtures water-cured for 28 days.

**Table 4-7: Test results for water absorption values for all LWC mixtures.**

| Mix | Description of mix | Water Absorption, % |
|---|---|---|
| M1 | Scoria as coarse aggregate | 8.85 |
| M2 | Scoria as coarse aggregate | 8.61 |
| M3 | Scoria as coarse aggregate | 7.95 |
| M4 | Scoria as coarse aggregate and 10% oil ash replacing sand | 11.41 |
| M5 | Polypropylene as coarse aggregate | 6.6 |
| M6 | Polypropylene as coarse aggregate with 10% oil ash replacing sand | 8.32 |
| M7 | 50% Scoria and 50% Polypropylene as coarse aggregate | 4.84 |
| M8 | 50% Limestone and 50% Polypropylene as coarse aggregate | 4.49 |
| M9 | Scoria as coarse aggregate and 10% rubber (2.5mm) replacing sand | 9.08 |
| M10 | Limestone as coarse aggregate and 10% rubber (2.5mm) replacing sand | 3.35 |

### 4.6.1 Scoria as coarse aggregate (M1, M2, M3)

The 28 days water absorption of mixtures M1, M2 and M3 is depicted for comparison in Figure 4.22. Among the three mixtures, the 28 days water absorption was the lowest for mix M3 with a cement content of 370 kg/m$^3$ and, CA/TA and FA/TA of 0.45 and 0.55, and the highest for mix M1 with a cement content of 400kg/m$^3$ and, CA/TA and FA/TA of 0.5 and 0.5, respectively. The 28 days water absorption for mixes M1, M2 and M3 was 8.85, 8.61 and 7.95 %, respectively.

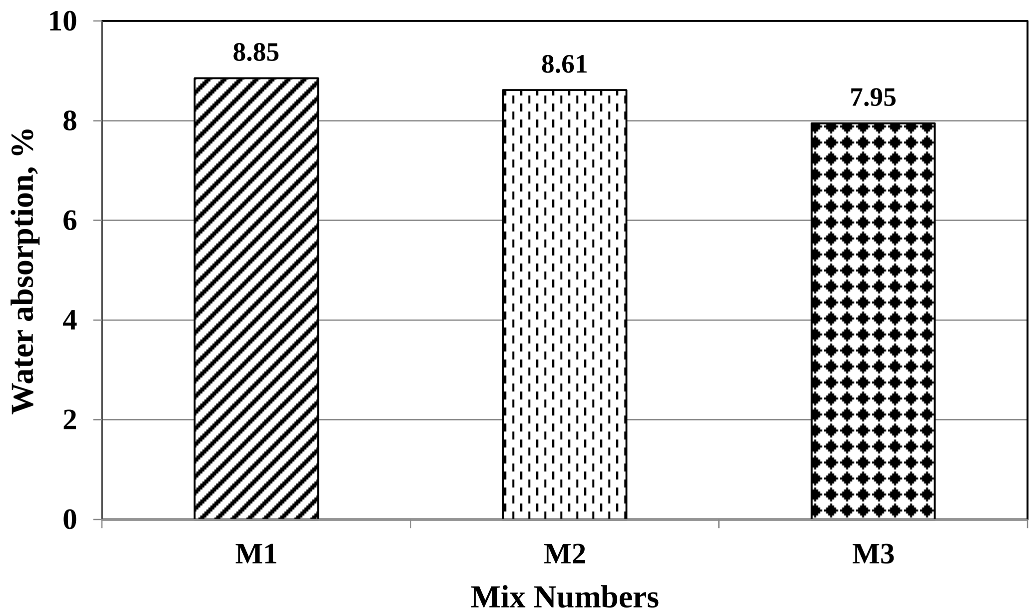


**Figure 4-22: Water absorption of mixtures M1, M2 and M3.**

### 4.6.2 Scoria with lightweight material as coarse aggregate (M4, M7, M9)

The 28 days water absorption of mixtures M4, M7 and M9 is depicted for comparison in Figure 4.23. Among the three mixtures, the 28 days water absorption was the lowest in mix M7 containing equal amounts of scoria and polypropylene as coarse aggregate and the highest in the mix M4 containing only scoria as coarse aggregate, respectively. The 28 days water absorption in mixes M4, M7 and M9 was 11.41, 4.84 and 9.08 %, respectively.

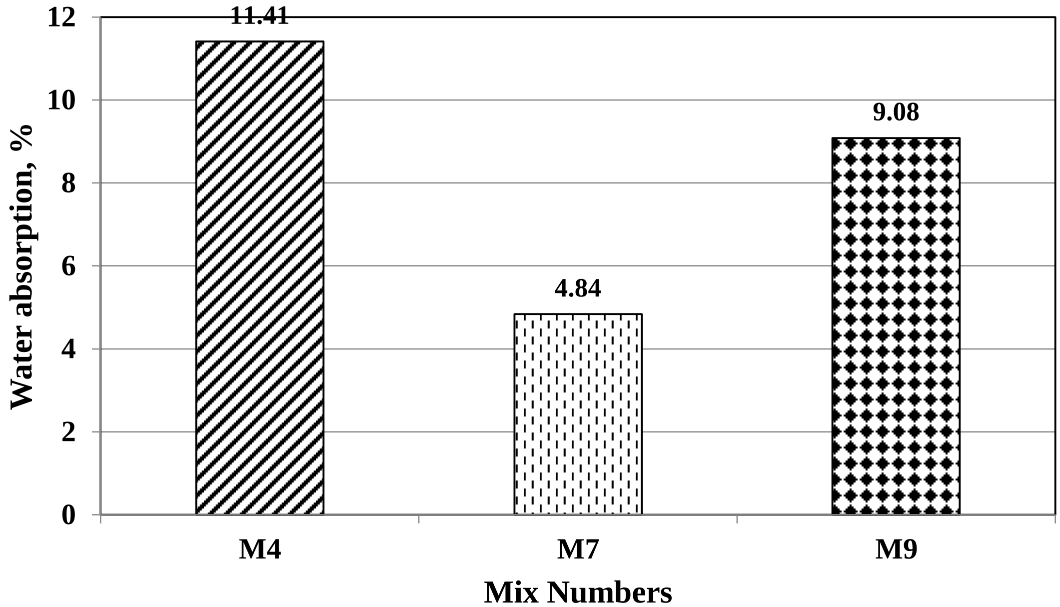


**Figure 4-23: Water absorption in mixtures M4, M7 and M9.**

### 4.6.3 Polypropylene as coarse aggregate (M5, M6, M7, M8)

The 28 days water absorption of mixtures M5, M6, M7 and M8 is depicted for comparison in Figure 4.24. Among the four mixtures, the 28 days water absorption was the lowest in mix M8 containing equal amounts of polypropylene and limestone as coarse aggregate, and the highest in mix M6 containing polypropylene as coarse aggregate and 10% oil ash replacing sand as fine aggregate, respectively. The water absorption in mixes M7 and M8 is almost same. The 28 days water absorption in mixes M5, M6, M7 and M8 was 6.6, 8.32, 4.84 and 4.49 %, respectively.

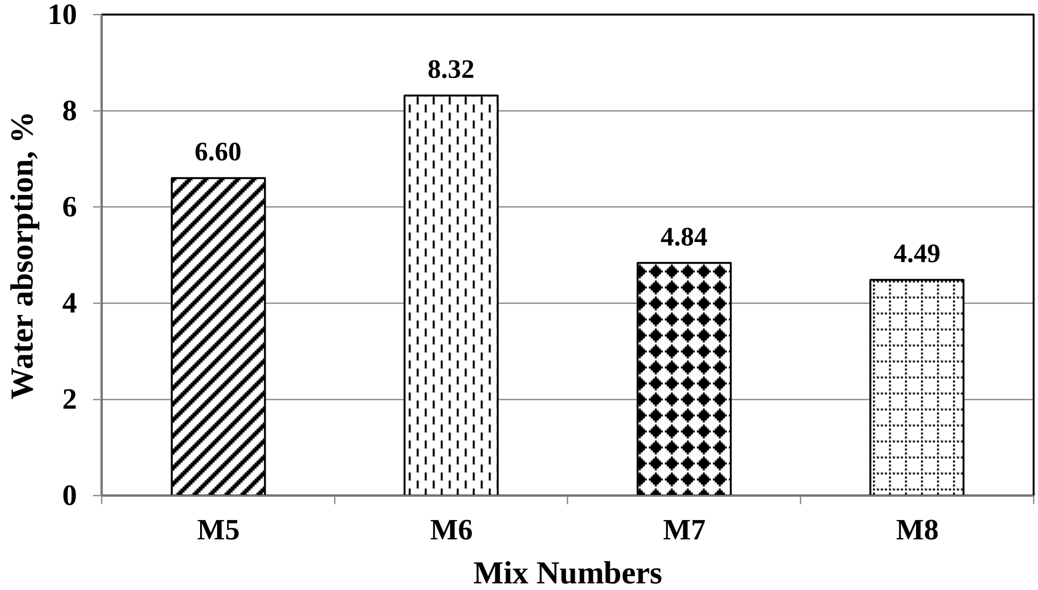


**Figure 4-24: Water absorption in mixtures M5, M6, M7 and M8.**

### 4.6.4 Rubber as replacement of sand (M9, M10)

The 28 days water absorption of mixtures M9 and M10 is depicted for comparison in Figure 4.25. Among the two mixtures, the 28 days water absorption was lower in mixture M10 containing limestone as coarse aggregate and 10% rubber replacing sand as fine aggregate, and higher in mixture M9 containing scoria as coarse aggregate and 10% rubber replacing sand as fine aggregate. The 28 days water absorption for mixtures M9 and M10 was 9.08 and 3.35 %, respectively.

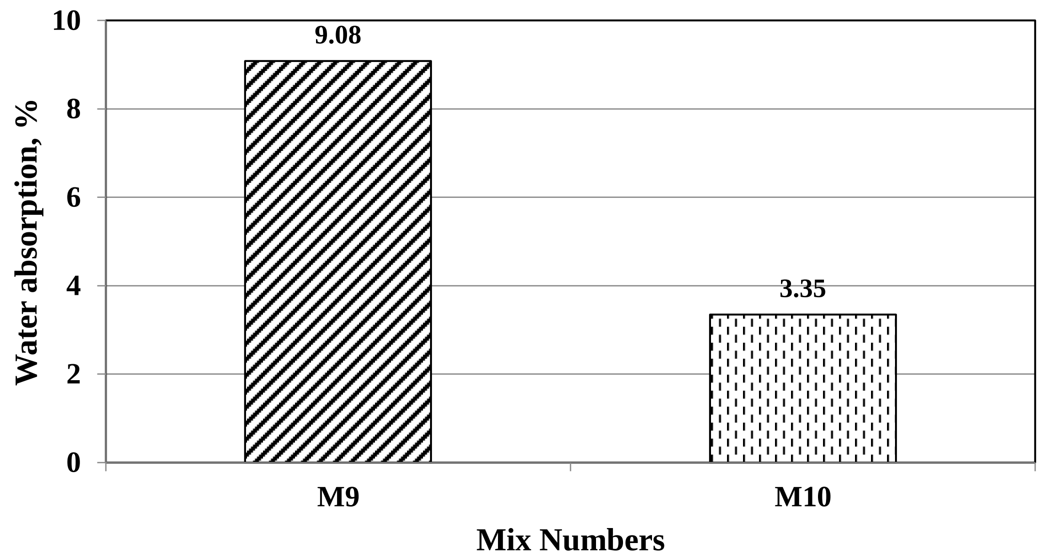


**Figure 4-25: Water absorption for mixtures M9 and M10.**

## 4.7 Drying Shrinkage

The drying shrinkage was measured over a period of about 57 days for mixtures M1, M2 and M3 on prism specimens of dimensions 25 x 25 x 275 mm after 14 days of water curing. Figure 4.8 shows the average drying shrinkage of mixtures M1, M2 and M3.

**Table 4-8: Average drying shrinkage for mixtures M1, M2 and M3.**

| Duration, days | Drying Shrinkage, microns | | |
|---|---|---|---|
| | M1 | M2 | M3 |
| 0 | 0 | 0 | 0 |
| 7 | 419 | 359 | 210 |
| 11 | 433 | 378 | 284 |
| 14 | 431 | 476 | 373 |
| 18 | 440 | 539 | 415 |
| 24 | 442 | 557 | 422 |
| 39 | 503 | 576 | 520 |
| 57 | 566 | 627 | 578 |

The drying shrinkage was measured over a period of about 63 days for mixtures M4 to M10 on prism specimens of dimensions 25 x 25 x 275 mm after 14 days of water curing. Figure 4.9 shows the average drying shrinkage values for mixtures M4 to M10.

**Table 4-9: Average drying shrinkage for mixtures M4 through M10.**

| Duration, days | Drying shrinkage, microns | | | | | | |
|---|---|---|---|---|---|---|---|
| | M4 | M5 | M6 | M7 | M8 | M9 | M10 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 365 | 225 | 211 | 269 | 189 | 150 | 230 |
| 6 | 506 | 281 | 279 | 363 | 257 | 204 | 307 |
| 13 | 639 | 370 | 414 | 401 | 339 | 258 | 347 |
| 17 | 646 | 429 | 471 | 447 | 395 | 295 | 401 |
| 20 | 658 | 447 | 515 | 497 | 449 | 330 | 457 |
| 24 | 674 | 461 | 550 | 546 | 486 | 349 | 499 |
| 30 | 707 | 499 | 569 | 604 | 517 | 391 | 529 |
| 45 | 763 | 546 | 630 | 682 | 549 | 461 | 637 |
| 63 | 805 | 637 | 726 | 862 | 577 | 511 | 668 |

### 4.7.1 Scoria as coarse aggregate (M1)

The average drying shrinkage strain values in this concrete mixture are depicted in Figure 4.26. The shrinkage strain values increased to above 400 microns in just 7 days. Then, the shrinkage strain increase was minimal for the next 14 days. After 24 days, there was a linear increase in shrinkage strain with respect to the period of exposure. After 57 days, the average shrinkage strain was 566 microns.

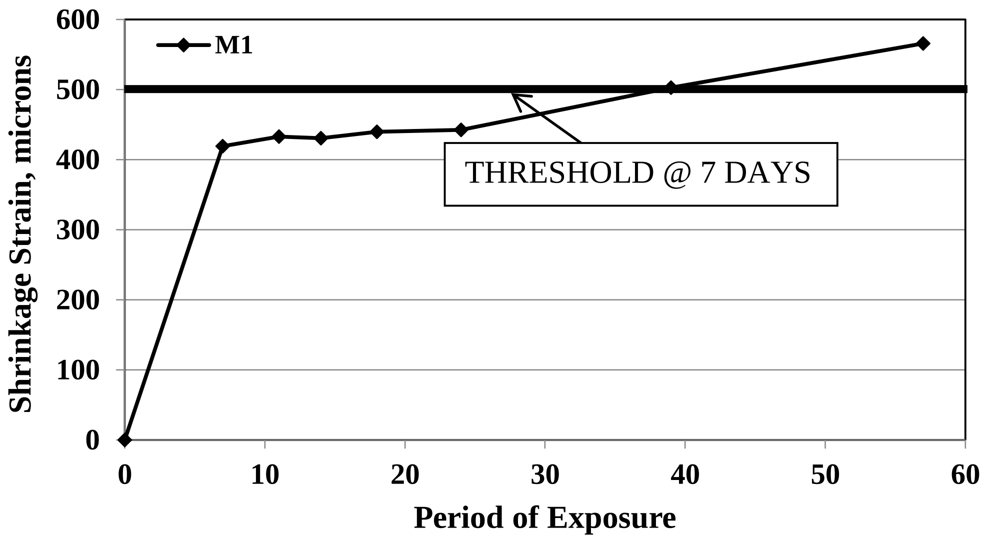


**Figure 4-26: Average drying shrinkage strain values for mixture M1.**

### 4.7.2 Scoria as coarse aggregate (M2)

The average drying shrinkage strain in the concrete mixture M2 is depicted in Figure 4.27. After 7 days, the average shrinkage strain reached above 350 microns. Between 18 and 39 days, there was a slight increase in the shrinkage strain values. After 57 days, the average shrinkage strain was 627 microns.

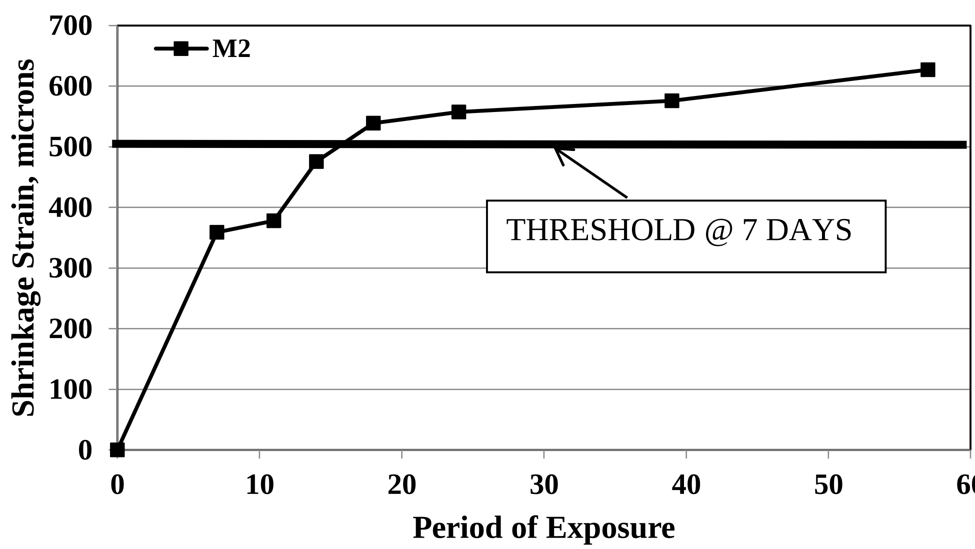


**Figure 4-27: Average drying shrinkage strain values for mixture M2.**

### 4.7.3 Scoria as coarse aggregate (M3)

The average drying shrinkage strain in this concrete mixture is depicted in Figure 4.28. The shrinkage strain increased almost linearly with duration for the first 14 days. After 57 days of exposure, the average shrinkage strain value was 578 microns.

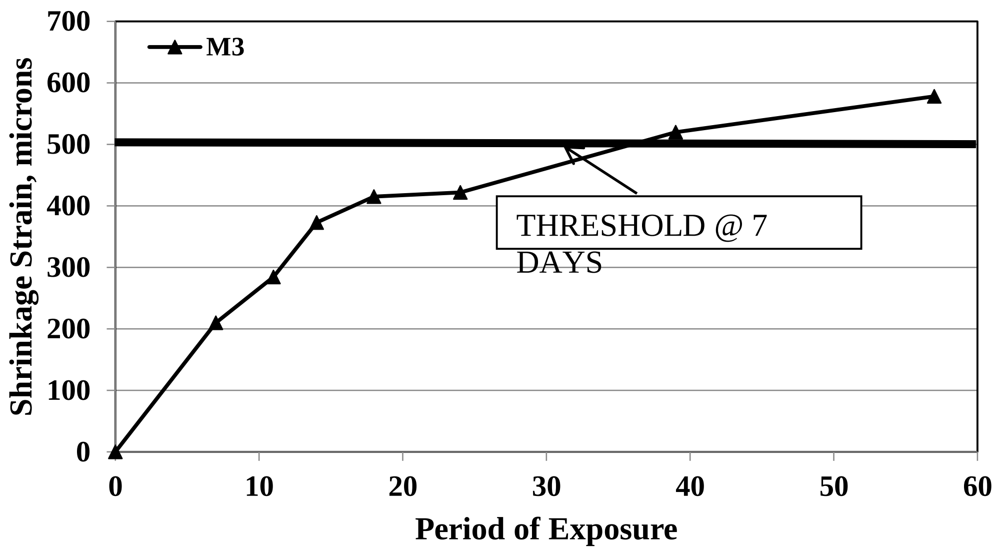


**Figure 4-28: Average drying shrinkage strain values for mixture M3.**

### 4.7.4 Scoria as coarse aggregate and 10% oil ash replacing sand (M4)

The average drying shrinkage strain in the concrete mixture M4 is depicted in Figure 4.29. The drying shrinkage strain increased drastically in the first 13 days. The shrinkage strain value was more than 500 microns after just 6 days. After 24 days, there was an almost linear increase in shrinkage strain. The average shrinkage strain value after 63 days of exposure was 805 microns.

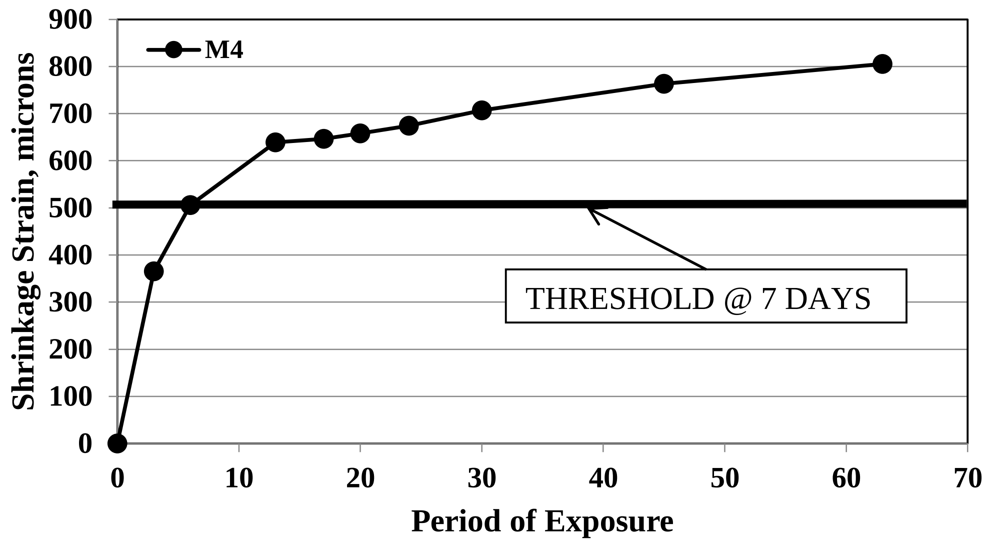


**Figure 4-29: Average drying shrinkage strain values for mixture M4.**

### 4.7.5 Polypropylene as coarse aggregate (M5)

The average drying shrinkage strain in this concrete mixture is depicted in Figure 4.30. The average shrinkage strain was 225 microns after 3 days. Shrinkage strain value crossed the threshold value of 500 microns after 30 days. After 63 days, the average shrinkage strain was 637 microns.

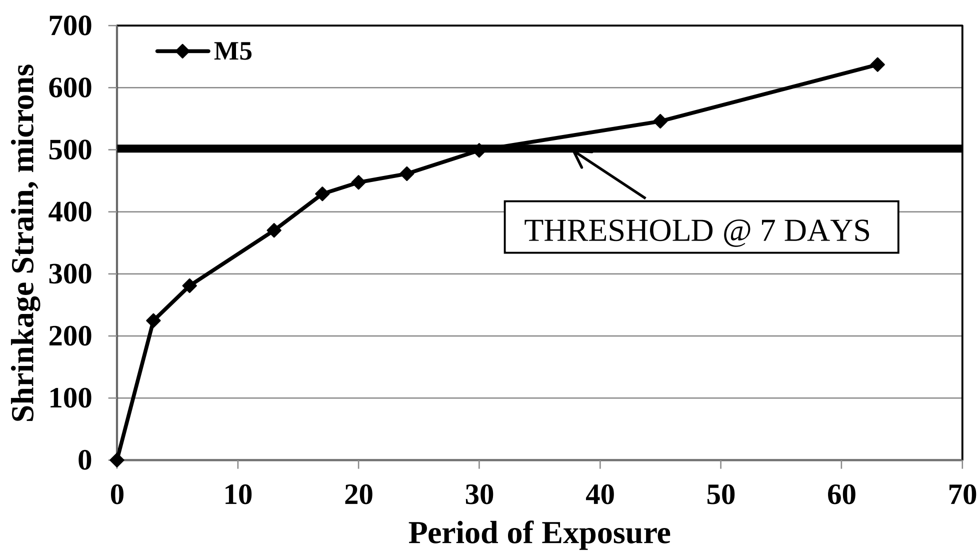


**Figure 4-30: Average drying shrinkage strain values for mixture M5.**

### 4.7.6 Polypropylene as coarse aggregate and 10% oil ash replacing sand (M6)

The average drying shrinkage strain in this concrete mixture is depicted in Figure 4.31. The average drying shrinkage strain was 211 microns after 3 days. Thereafter, the increase in shrinkage strain values was almost linear. The shrinkage strain value crossed the threshold value of 500 microns after 19 days. After 63 days, the average shrinkage strain value was 726 microns.

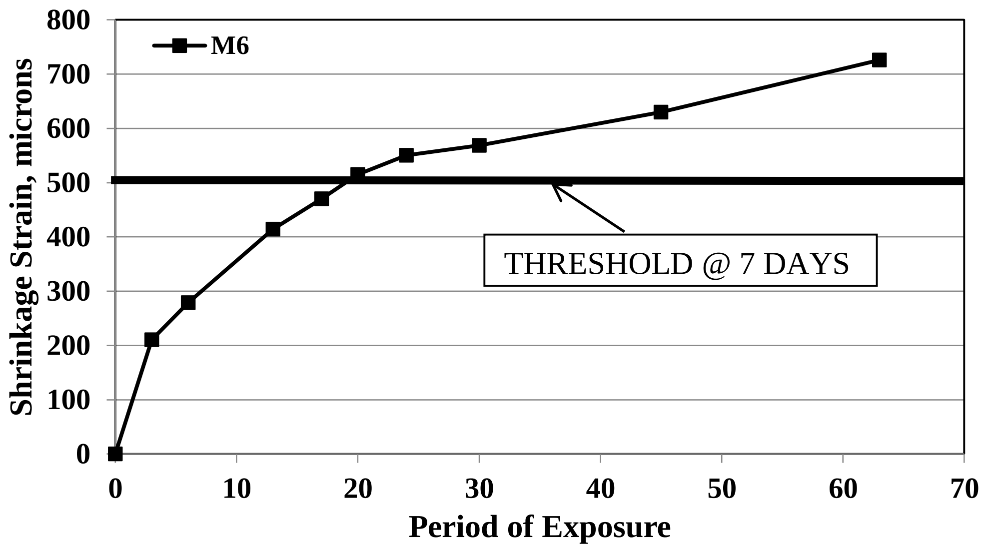


**Figure 4-31: Average drying shrinkage strain values for mixture M6.**

### 4.7.7 Scoria and polypropylene as coarse aggregate (M7)

The average drying shrinkage strain in the concrete mixture M7 is depicted in Figure 4.32. The average shrinkage strain was 269 microns after 3 days. From 13 to 30 days, a linear increase was noticed in the shrinkage values. The shrinkage strain value crossed the threshold value of 500 microns after 20 days. After 30 days, a slight relaxation in the increment of shrinkage strain was noted. After 63 days, the average shrinkage strain value was 862 microns.

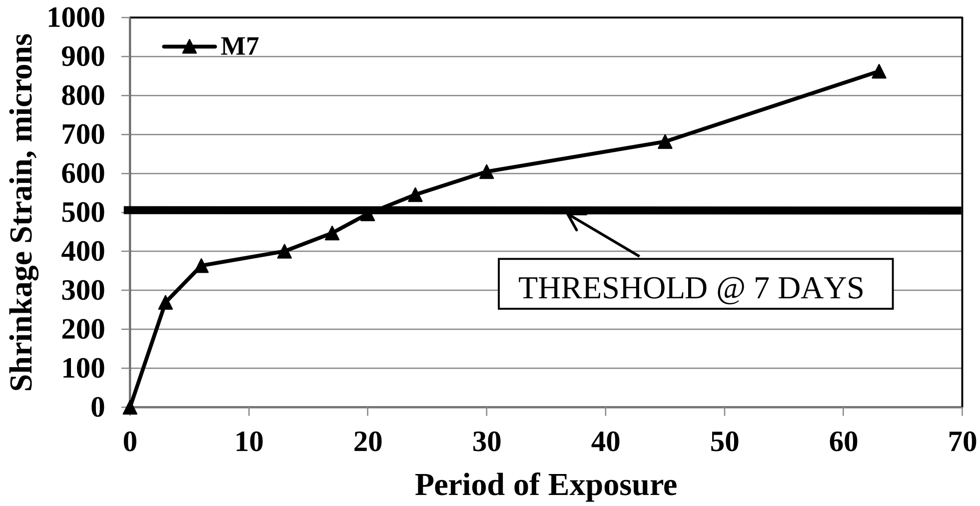


**Figure 4-32: Average drying shrinkage strain values for mixture M7.**

### 4.7.8 Limestone and polypropylene as coarse aggregate (M8)

The average drying shrinkage strain in this concrete mixture is depicted in Figure 4.33. After 3 days, the average shrinkage strain was 189 microns. There was a regular increase in the shrinkage strain values till 24 days. After 24 days, a linear increase in the values was noticed. The shrinkage strain value crossed the threshold value of 500 microns after 26 days. After 63 days, the average shrinkage strain value was 577 microns.

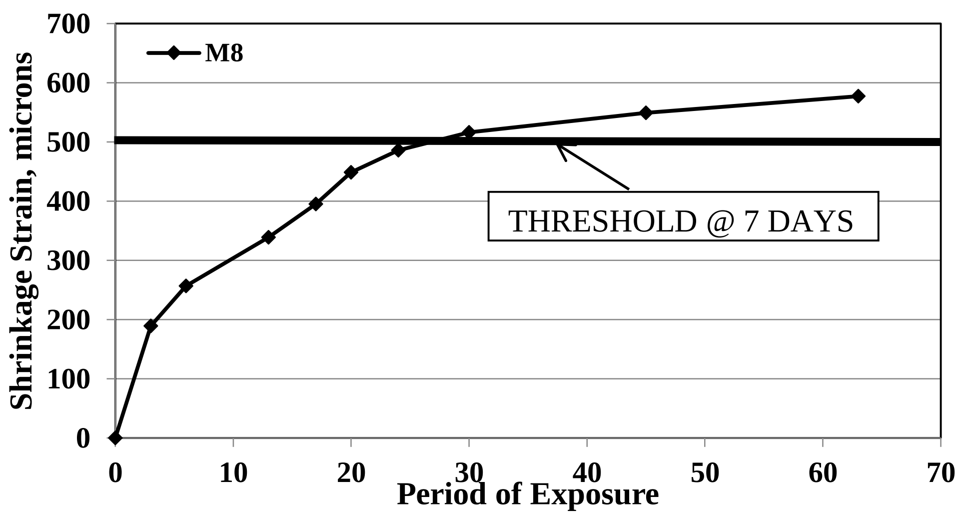


**Figure 4-33: Average drying shrinkage strain values for mixture M8.**

### 4.7.9 Scoria as coarse aggregate and 10% addition of rubber replacing sand (M9)

The average drying shrinkage strain in this concrete mixture is depicted in Figure 4.34. After 3 days, the average drying shrinkage strain was 150 microns. After 13 days, the shrinkage strain values increased at a slightly decreasing rate with respect to the period of exposure. The shrinkage strain value crossed the threshold value of 500 microns after 61 days. After 63 days, the average shrinkage strain was 511 microns. This is the lowest in all the ten LWC mixtures investigated in this study.

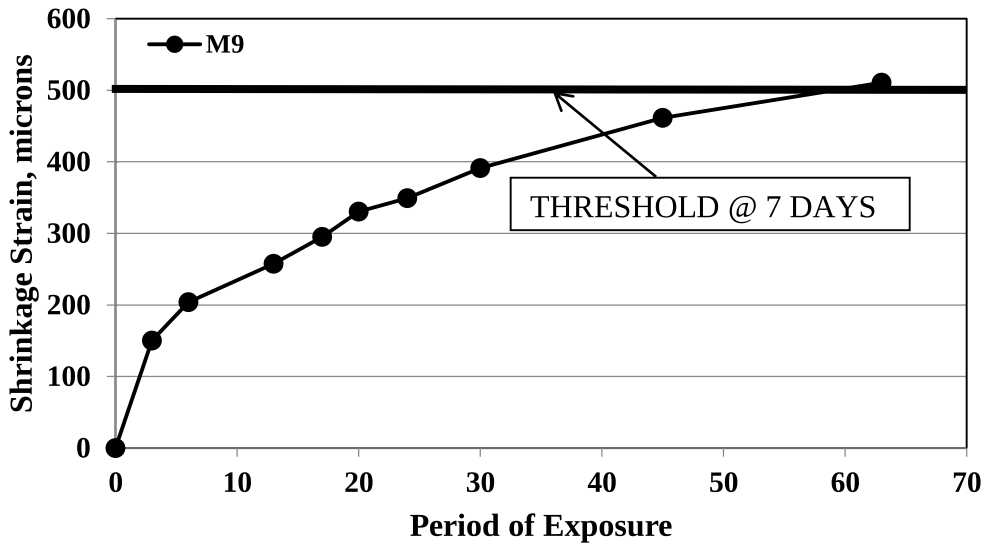


**Figure 4-34 Average drying shrinkage strain values for mixture M9.**

### 4.7.10 Limestone and rubber as coarse aggregate and 10% rubber replacing sand (M10)

The average drying shrinkage strain in this concrete mixture is depicted in Figure 4.35. After 3 days, the average drying shrinkage strain was 230 microns. The shrinkage strain value crossed the threshold value of 500 microns after 24 days. The increase in the values for the last 18 days was almost minimal. After 63 days, the average drying shrinkage strain values for this mix was 668 microns.

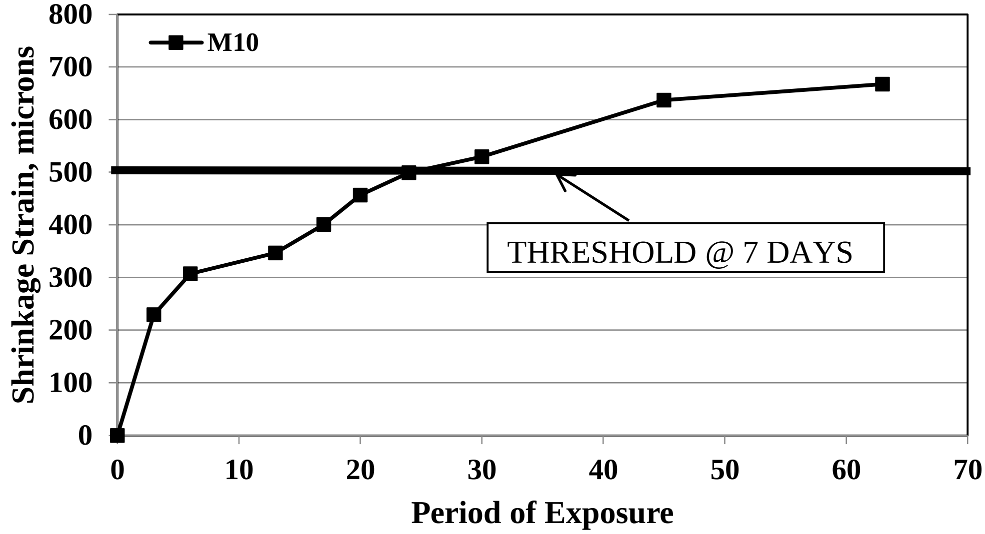


**Figure 4-35: Average drying shrinkage strain values for mixture M10.**

## 4.8 Chloride Permeability

The average values of chloride permeability of all the mixtures, water cured for 28 days, are listed in Table 4.10 and the standard classification of chloride permeability values is shown in Table 4.11.

**Table 4-10: Average chloride permeability after 28 days of curing.**

| Mix # | Average Chloride Permeability, Coulombs | Permeability Classification |
|---|---|---|
| M1 | 7854 | High |
| M2 | 6048 | High |
| M3 | 7163 | High |
| M4 | 10303 | High |
| M5 | 2456 | Moderate |
| M6 | 3444 | Moderate |
| M7 | 4704 | High |
| M8 | 2731 | Moderate |
| M9 | 6191 | High |
| M10 | 3687 | Moderate |

**Table 4-11: Standard classification of Chloride permeability as per ASTM C1202.**

| Charge passed, Coulombs | Concrete Permeability Classification |
|---|---|
| <1000 | Very Low |
| 1000-2000 | Low |
| 2000-4000 | Moderate |
| >4000 | High |

### 4.8.1 Scoria as coarse aggregate (M1, M2, M3)

The chloride permeability values for mixtures M1, M2 and M3 is depicted for comparison in Figure 4.36. The permeability of all the three mixtures is high according to ASTM C1202 classification. Among the three mixtures, the chloride permeability was the lowest in mixture M2 and the highest in mixture M1. The chloride permeability values for mixtures M1, M2 and M3 was 7854, 6048 and 7163 Coulombs, respectively.

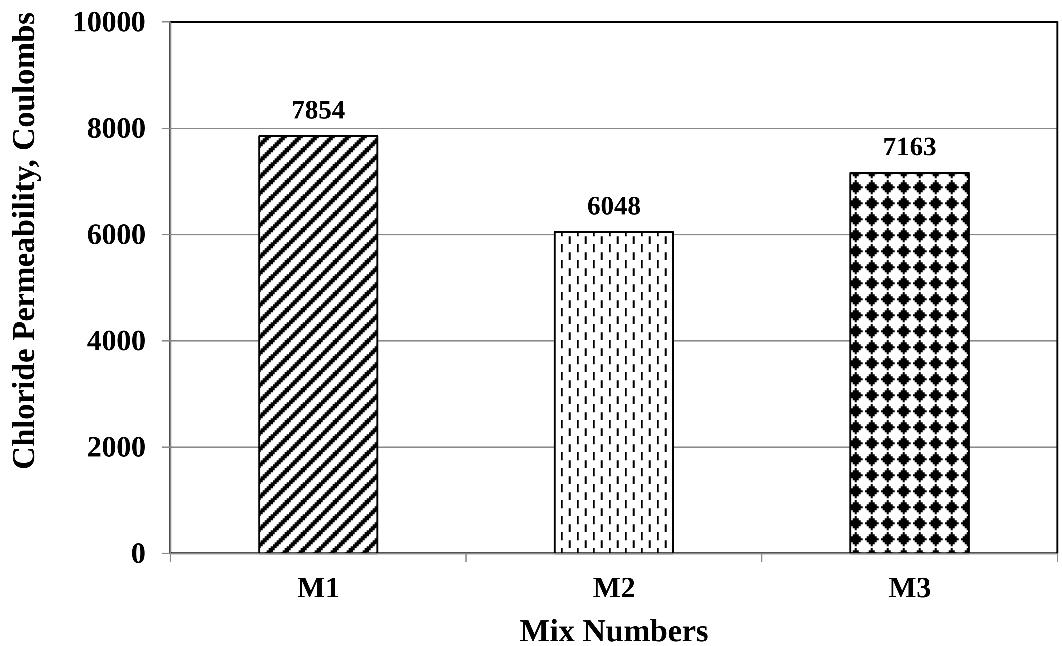


**Figure 4-36: Average chloride permeability of mixtures M1, M2 and M3.**

### 4.8.2 Scoria with lightweight material as coarse aggregate (M4, M7, M9)

The chloride permeability values of mixtures M4, M7 and M9 is depicted for comparison in Figure 4.37. Again the chloride permeability was high as per ASTM C1202 classification. Among the three mixtures, the chloride permeability value was the lowest in mixture M7 containing equal quantities of scoria and polypropylene as coarse aggregate and highest in mix M4 containing scoria with 10% oil ash as replacement of sand. The chloride permeability values for mixtures M4, M7 and M9 was 10303, 4704 and 6191 Coulombs, respectively.

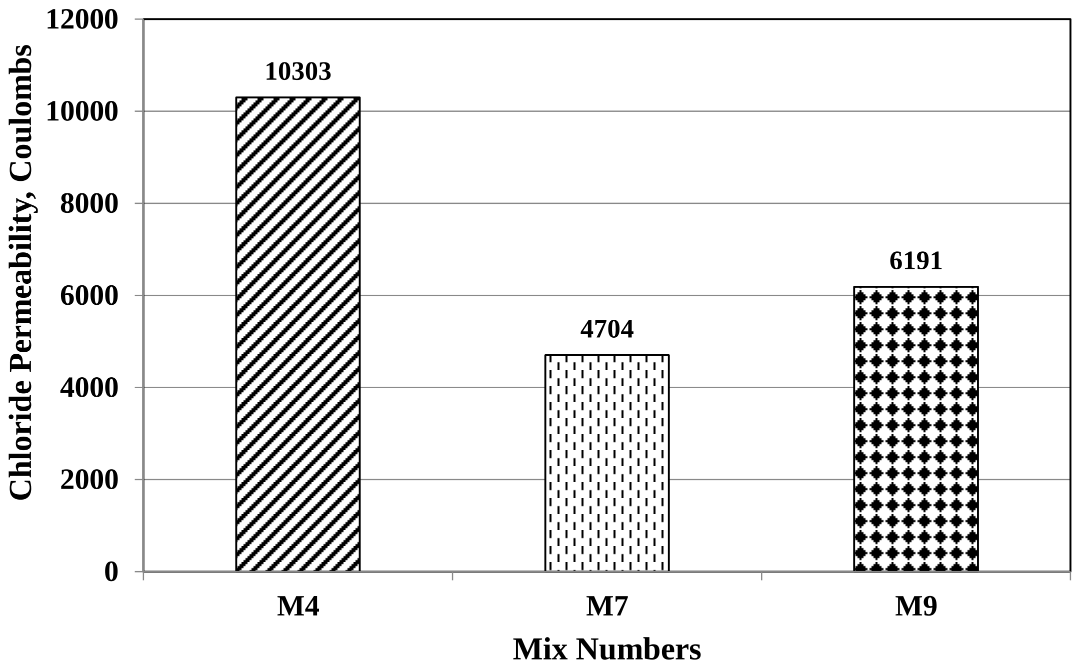


**Figure 4-37: Average chloride permeability of mixtures M4, M7 and M9.**

### 4.8.3 Polypropylene as coarse aggregate (M5, M6, M7, M8)

The chloride permeability of mixtures M5, M6, M7 and M8 is depicted for comparison in Figure 4.38. The chloride permeability was moderate in mixtures M5, M6 and M8, and high in mix M7, according to ASTM C1202 classification. Among the four mixtures, the chloride permeability value was the lowest in mix M5 containing only polypropylene as coarse aggregate and the highest in mix M7 containing equal quantities of polypropylene and scoria as coarse aggregate. The average chloride permeability values for mixtures M5, M6, M7 and M8 were 2456, 3444, 4704 and 2731 Coulombs, respectively.

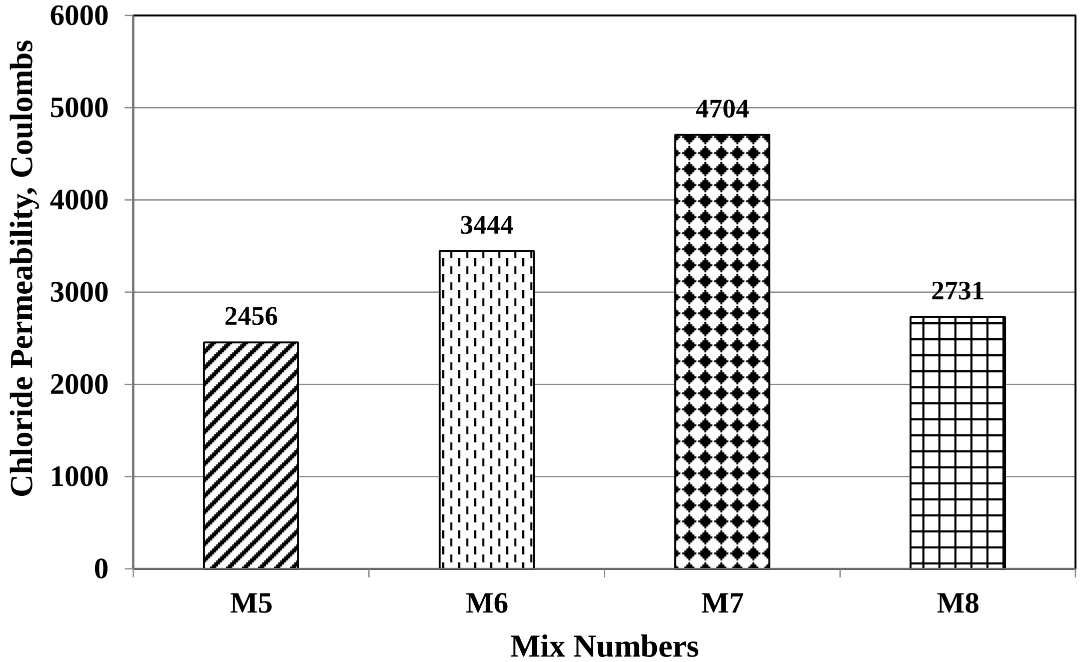


**Figure 4-38: Average chloride permeability of mixtures M5, M6, M7 and M8.**

### 4.8.4 Rubber as replacement of sand (M9, M10)

The chloride permeability values for mixtures M9 and M10 is depicted for comparison in Figure 4.39. Among the two mixtures, the chloride permeability was the lowest in mixture M10 containing limestone as coarse aggregate and 10% rubber replacing sand as fine aggregate and the highest in mix M9 containing scoria as coarse aggregate and 10% addition of rubber replacing sand as fine aggregate. The chloride permeability values for M9 and M10 was 6191 and 3687 Coulombs, respectively. As per ASTM C1202 classification, the chloride permeability was high in mix M9 and moderate in mixture M10.

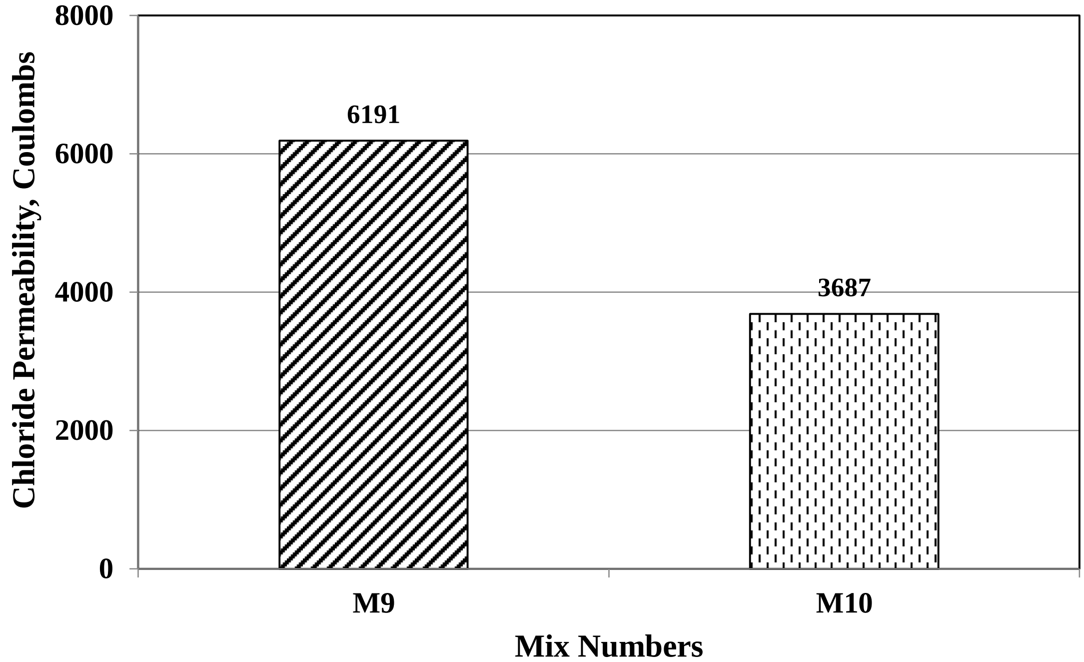


**Figure 4-39: Average chloride permeability of mixtures M9 and M10.**

## 4.9 Corrosion Potentials

### 4.9.1 Scoria as coarse aggregate (M1)

The average corrosion potential values in this concrete mixture are depicted in Figure 4.40. The potentials were more negative than the ASTM C 876 threshold value of -270 mV SCE since the time of immersion in the chloride solution. The potentials decreased (became more negative) with time of exposure in the chloride solution in these concrete specimens.

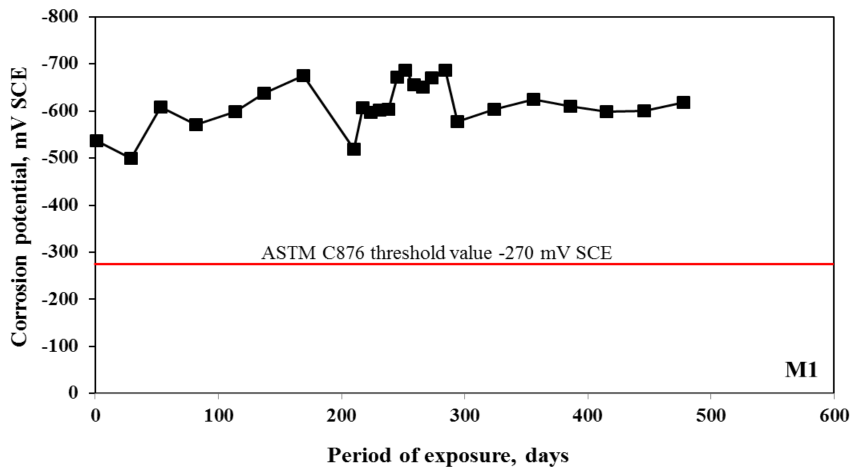


**Figure 4-40: Average corrosion potential variation of mix M1.**

### 4.9.2 Scoria as coarse aggregate (M2)

The average corrosion potential values in this concrete mixture are depicted in Figure 4.41. The potentials were more negative than the ASTM C 876 threshold value of -270 mV SCE since the time of immersion in the chloride solution. The corrosion potential value at 1 day was -416 mV SCE. The potentials decreased initially for the first 82 days and then stabilized to remain in the range of -660 and -590 mV SCE after about 480 days of exposure.

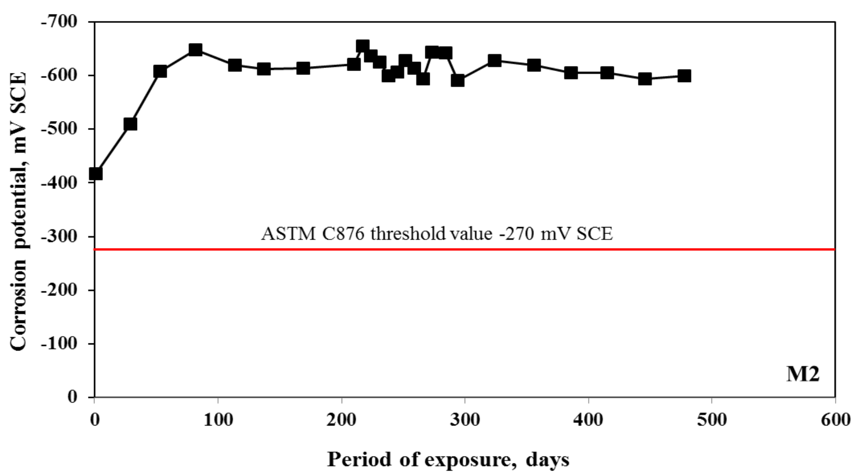


**Figure 4-41: Average corrosion potential variation of mix M2.**

### 4.9.3 Scoria as coarse aggregate (M3)

The average corrosion potential values in this concrete mixture are depicted in Figure 4.42. The corrosion potential value at 1 day was -167 mV SCE. Thereafter, the corrosion potentials decreased (became more negative) to -574 mV SCE after 53 days. The corrosion potentials crossed the threshold value of -270 mV SCE after 16 days. After 53 days, the corrosion potentials remained in the range of -750 and -510 mV SCE. After 294 days of exposure, the corrosion potentials variation was almost linear.

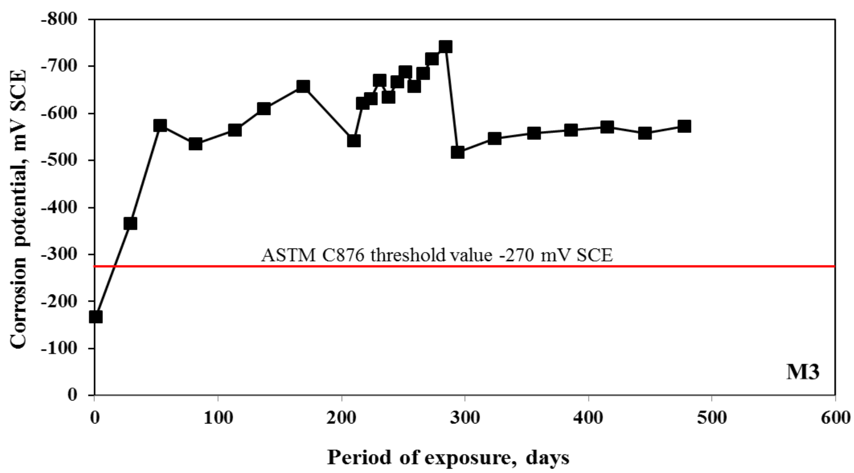


**Figure 4-42: Average corrosion potential variation of mix M3.**

### 4.9.4 Scoria as coarse aggregate and 10% oil ash replacing sand (M4)

The average corrosion potential values in this concrete mixture are depicted in Figure 4.43. The potentials were more negative than the ASTM C 876 threshold value of -270 mV SCE since the time of immersion in the chloride solution. The corrosion potential value at 3 day was -304 mV SCE. After 10 days, the corrosion potential values stabilized in the range of -660 and -570 mV SCE.

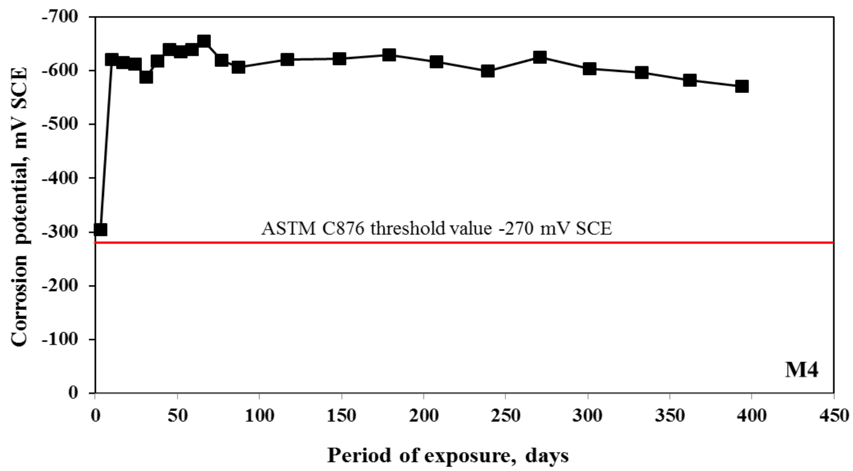


**Figure 4-43: Average corrosion potential variation of mix M4.**

### 4.9.5 Polypropylene as coarse aggregate (M5)

The average corrosion potential values in this concrete mixture are depicted in Figure 4.44. The corrosion potential value at 3 days was -189 mV SCE. Thereafter, the corrosion potentials jumped to -564 mV SCE after 10 days. The corrosion potentials crossed the threshold value of -270 mV SCE after 5 days. After 10 days, the corrosion potentials remained in the range of -640 and -530 mV SCE. After 87 days, the corrosion potentials variation was almost linear.

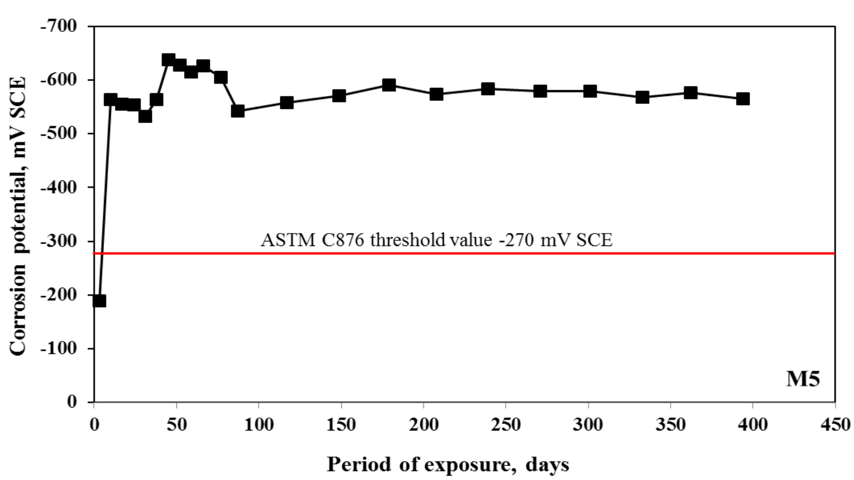


**Figure 4-44: Average corrosion potential variation of mix M5.**

### 4.9.6 Polypropylene as coarse aggregate and 10% oil ash replacing sand (M6)

The average corrosion potential values in this concrete mixture are depicted in Figure 4.45. The corrosion potential value at 3 days was -287 mV SCE which is very close to but less than (more negative than) the threshold value of -270 mV SCE. Thereafter, the corrosion potentials jumped to -592 mV SCE after 10 days. After 10 days, the corrosion potentials remained in the range of -610 and -520 mV SCE. After 117 days, the corrosion potentials variation was almost linear.

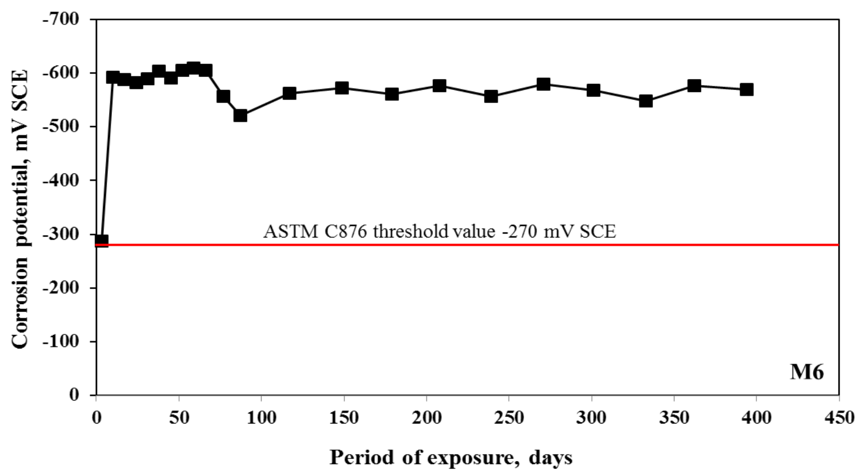


**Figure 4-45: Average corrosion potential variation of mix M6.**

### 4.9.7 Scoria and polypropylene as coarse aggregate (M7)

The average corrosion potential values in this concrete mixture are depicted in Figure 4.46. The potentials were more negative than the ASTM C 876 threshold value of -270 mV SCE since the time of immersion in the chloride solution. The corrosion potential value at 3 day was -293 mV SCE. After 45 days, the corrosion potentials varied in the range of -580 and -500 mV SCE.

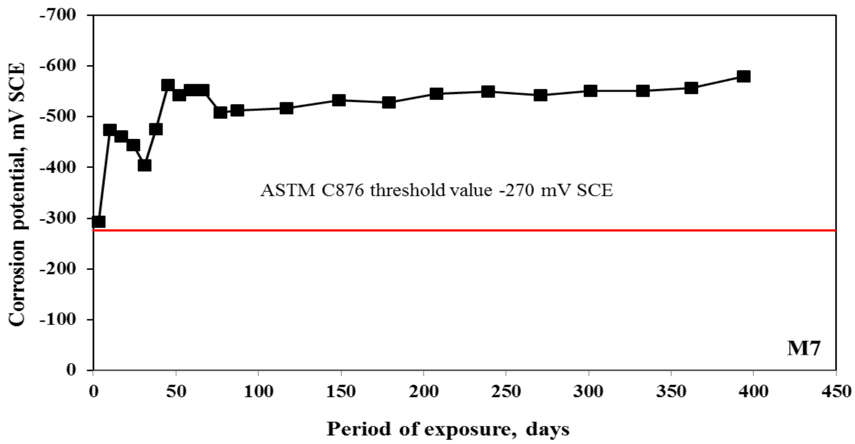


**Figure 4-46: Average corrosion potential variation of mix M7.**

### 4.9.8 Limestone and polypropylene as coarse aggregate (M8)

The average corrosion potential values in this concrete mixture are depicted in Figure 4.47. The potentials were more negative than the ASTM C 876 threshold value of -270 mV SCE since the time of immersion in the chloride solution. The corrosion potential value at 3 day was -360 mV SCE. Thereafter, the potentials decreased (became more negative) to reach a minimum value of -593 mV SCE after 45 days. After 45 days, the corrosion potentials varied in the range of -600 and -500 mV SCE. After 87 days, there was no significant variation in the corrosion potential values.

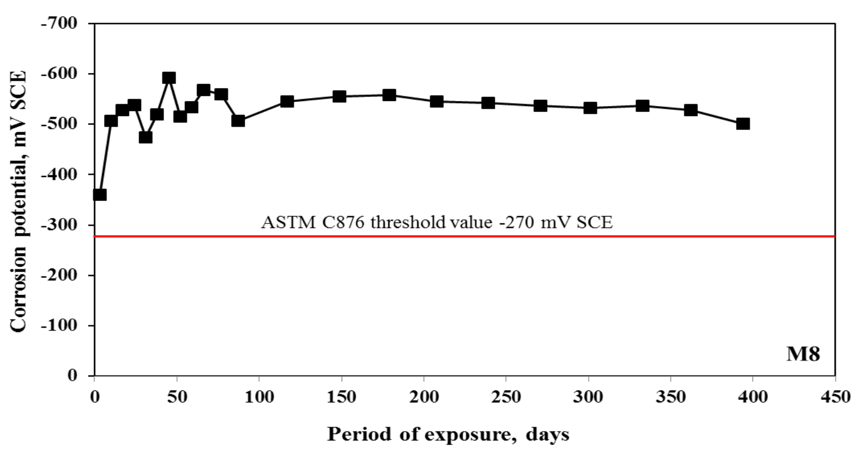


**Figure 4-47: Average corrosion potential variation of mix M8.**

#### 4.9.9 Scoria as coarse aggregate and 10% addition of rubber replacing sand (M9)

The average corrosion potential values in this concrete mixture are depicted in Figure 4-48. The potentials were more negative than the ASTM C 876 threshold value of -270 mV SCE since the time of immersion in the chloride solution. The corrosion potential value at 3 day was -524 mV SCE. After 45 days, the corrosion potentials reached a minimum value of -595 mV SCE.

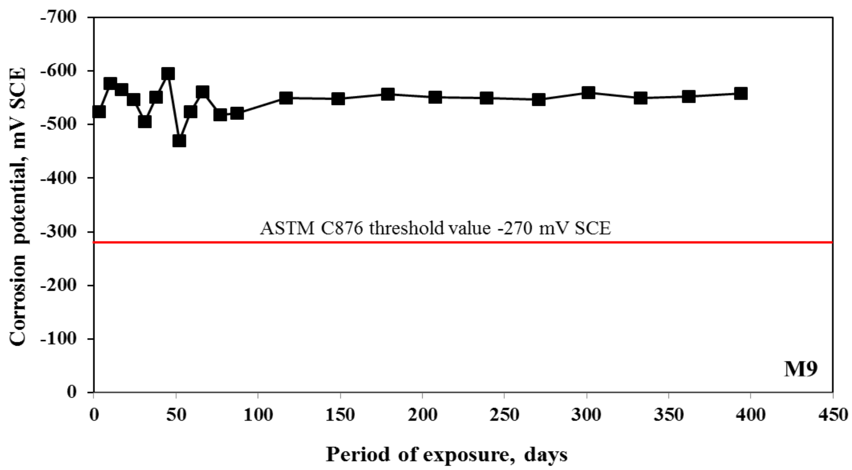


**Figure 4-48: Average corrosion potential variation of mix M9.**

#### 4.9.10 Limestone and rubber as coarse aggregate and 10% rubber replacing sand

The average corrosion potential values in this concrete mixture are depicted in Figure 4.49. The potentials were more negative than the ASTM C 876 threshold value of -270 mV SCE since the time of immersion in the chloride solution. The corrosion potential value at 3 day was -458 mV SCE. There was a linear decrease in potential values upto 45 days.

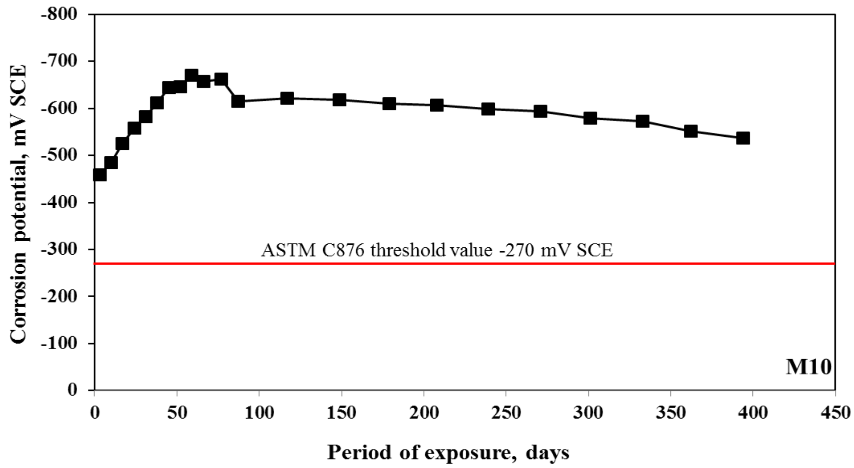


**Figure 4-49: Average corrosion potential variation of mix M10.**

## 4.10 Corrosion Current Density

### 4.10.1 Scoria as coarse aggregate (M1)

The average corrosion current density (Icorr) values in this concrete mixture are depicted in Figure 4.50. At 210 days, the average Icorr was 0.258 $\mu A/cm^2$, which is below the threshold value of 0.3 $\mu A/cm^2$. After approx. 212 days, the Icorr values crossed the threshold value. Thereafter, the Icorr value increased to reach a value of 1.210 $\mu A/cm^2$ after 290 days. After 604 days, the average corrosion current density (Icorr) value was 1.472 $\mu A/cm^2$.

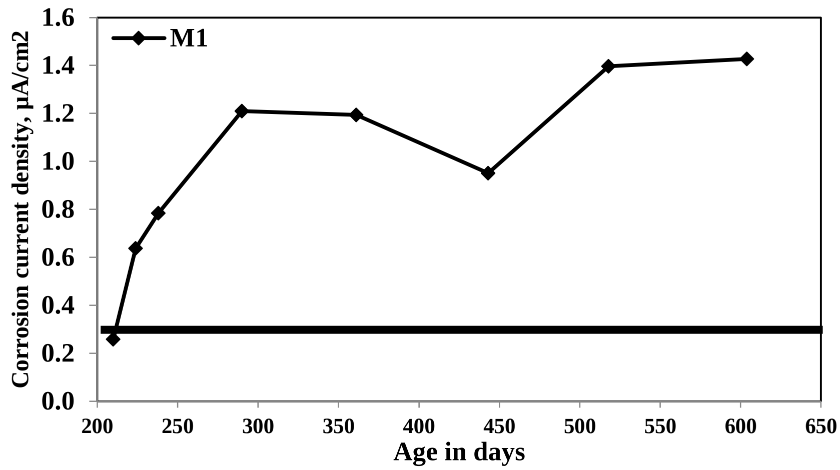


**Figure 4-50: Average Icorr variation in Mix M1.**

### 4.10.2 Scoria as coarse aggregate (M2)

The average corrosion current density (Icorr) values in this concrete mixture are depicted in Figure 4.51. At 210 days, the average Icorr of the three specimen was 0.569 µA/cm$^2$; which is well above the threshold value of 0.3 µA/cm$^2$ for initiation of corrosion. Thereafter, the Icorr values increased to reach a value of 0.898 µA/cm$^2$ after 290 days. After 361 days, the increase in the Icorr values was almost linear. After 604 days, the average Icorr value was 1.325 µA/cm$^2$.

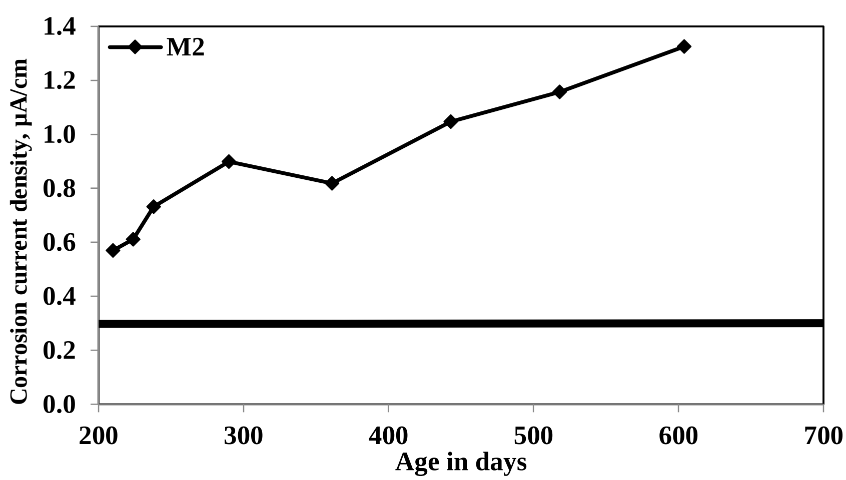


**Figure 4-51: Average Icorr variation in Mix M2.**

### 4.10.3 Scoria as coarse aggregate (M3)

The average corrosion current density (Icorr) values in this concrete mixture are depicted in Figure 4.52. At 210 days, the average Icorr value was 0.343 µA/cm$^2$; which is more than the threshold value of 0.3 µA/cm$^2$ for initiation of corrosion. Thereafter, the Icorr values increased to reach a value of 0.925 µA/cm$^2$ after 238 days. After 443 days, there was a slight decrease in the Icorr values. After 604 days, the average Icorr value was 1.194 µA/cm$^2$.

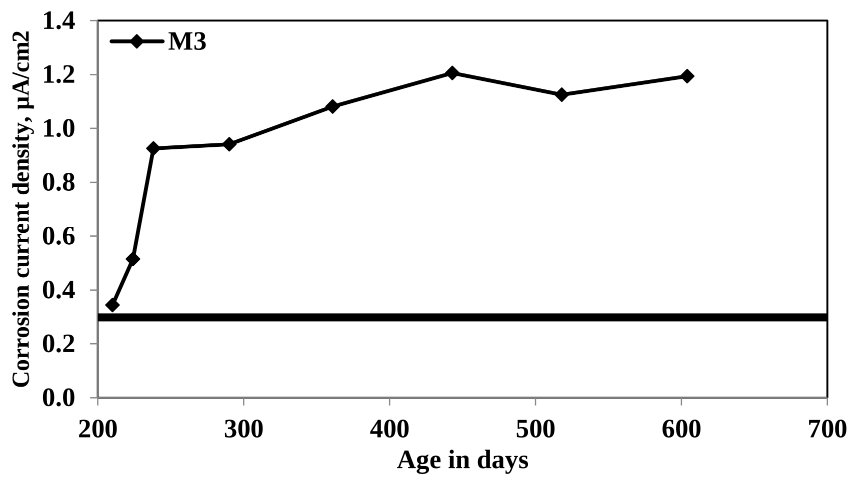


**Figure 4-52: Average Icorr variation in Mix M3.**

### 4.10.4 Scoria as coarse aggregate and 10% oil ash replacing sand (M4)

The average corrosion current density (Icorr) values in this concrete mixture are depicted in Figure 4.53. At 3 days, the average Icorr value was 0.17 µA/cm$^2$, which is below the threshold value of 0.3 µA/cm$^2$ for initiation of corrosion. At approx. 12 days, the Icorr value crossed the threshold value. Thereafter, the Icorr values increased to reach a value of 0.418 µA/cm$^2$ after 31 days. After 31 days, there was a sharp decline in the Icorr values. After 83 days, the Icorr values remained below the threshold value. After 397 days, the average Icorr value was 0.223 µA/cm$^2$.

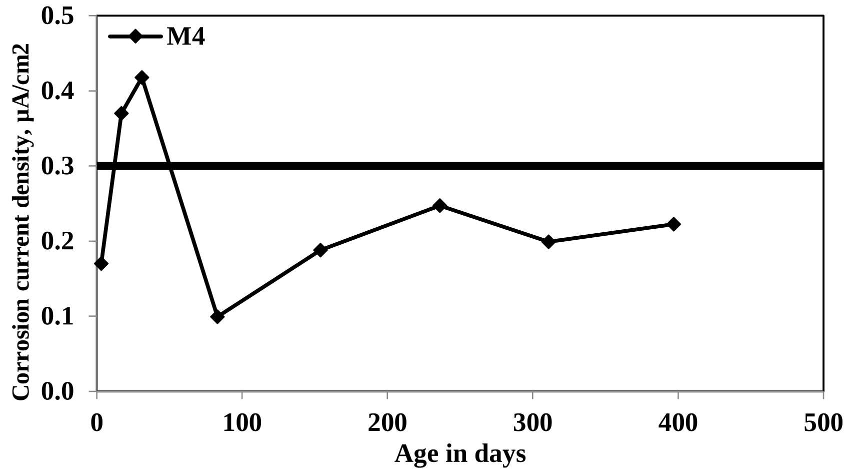


**Figure 4-53: Average Icorr variation in Mix M4.**

### 4.10.5 Polypropylene as coarse aggregate (M5)

The average corrosion current density (Icorr) values in this concrete mixture are depicted in Figure 4.54. At 3 days, the average Icorr value was 0.011 µA/cm$^2$, which is below the threshold value of 0.3 µA/cm$^2$ for initiation of corrosion. The Icorr value increased to cross the threshold value at 278 days. After 397 days, the average Icorr value was 0.391 µA/cm$^2$.

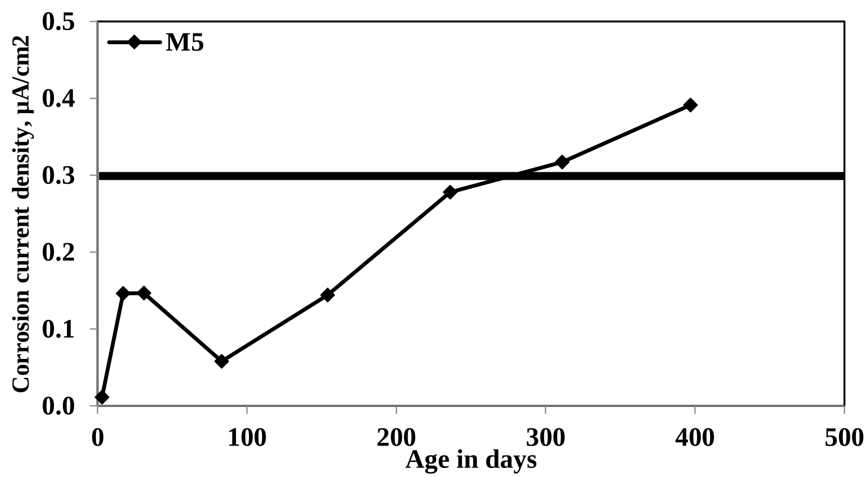


**Figure 4-54: Average Icorr variation in Mix M5.**

### 4.10.6 Polypropylene as coarse aggregate and 10% oil ash replacing sand (M6)

The average corrosion current density (Icorr) values in this concrete mixture are depicted in Figure 4.55. At 3 days, the average Icorr value was 0.102 µA/cm$^2$, which is below the threshold value of 0.3 µA/cm$^2$ for initiation of corrosion. At approx. 21 days, the Icorr value crossed the threshold value. After 31 days, there was a sharp decline in the Icorr values. The Icorr values remained below the threshold value. After 397 days, the average Icorr value was 0.256 µA/cm$^2$.

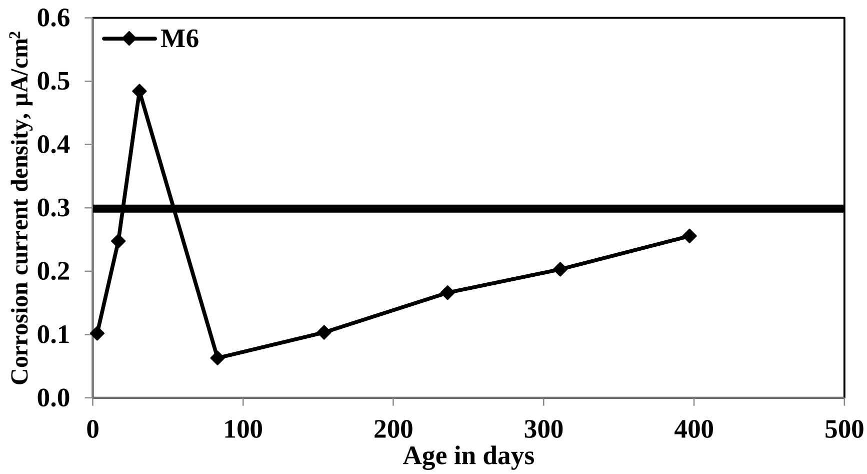


**Figure 4-55: Average Icorr variation in Mix M6**

### 4.10.7 Scoria and polypropylene as coarse aggregate (M7)

The average corrosion current density (Icorr) values in this concrete mixture are depicted in Figure 4.56. At 3 days, the average Icorr value was 0.011 µA/cm$^2$, which is below the threshold value of 0.3 µA/cm$^2$ for initiation of corrosion. The Icorr value decreased to reach 0.149 µA/cm$^2$ at 83 days. The Icorr value increased to cross the threshold value at 136 days. After 397 days, the average Icorr value was 0.764 µA/cm$^2$.

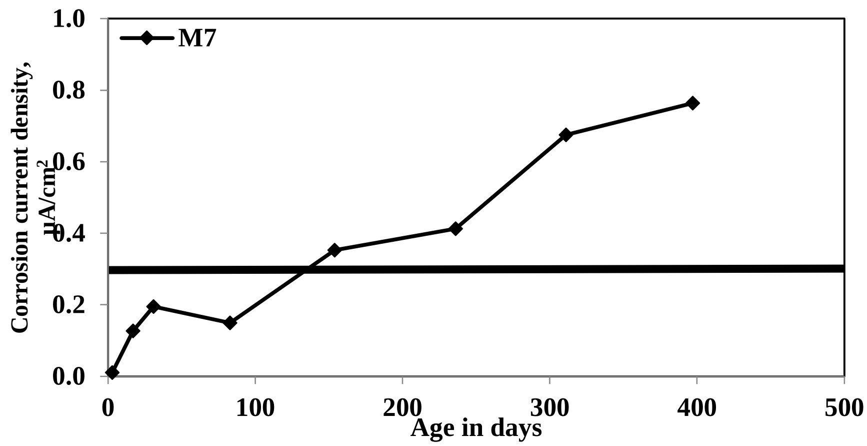


**Figure 4-56: Average Icorr variation in Mix M7.**

### 4.10.8 Limestone and polypropylene as coarse aggregate (M8)

The average corrosion current density (Icorr) values in this concrete mixture are depicted in Figure 4.57. At 3 days, the average Icorr value was 0.183 µA/cm$^2$, which is below the threshold value of 0.3 µA/cm$^2$ for initiation of corrosion. The Icorr values increased after 3 days and crossed the threshold value after 30 days. After 31 days, the Icorr values decreased to fall below the threshold value till 83 days. After 83 days, the Icorr values again increased to cross the threshold value. After 397 days, the average Icorr value was 0.661 µA/cm$^2$.

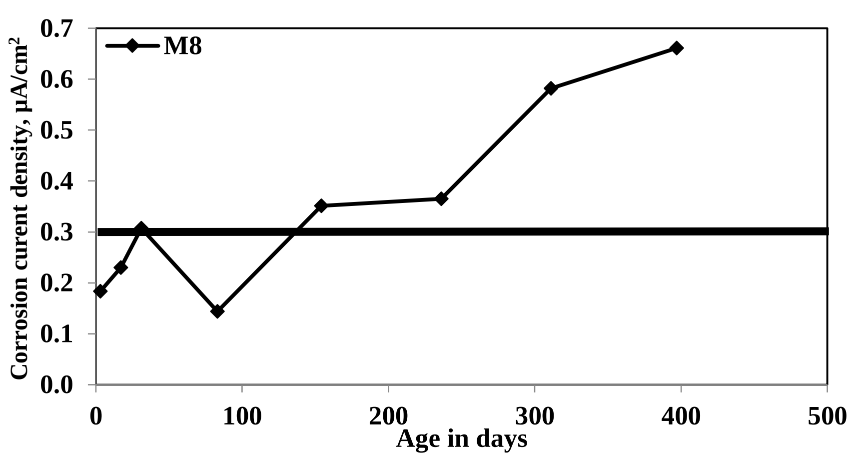


**Figure 4-57: Average Icorr variation in Mix M8.**

### 4.10.9 Scoria as coarse aggregate and 10% addition of rubber replacing sand (M9)

The average corrosion current density (Icorr) values in this concrete mixture are depicted in Figure 4.58. At 3 days, the average Icorr was 0.287 µA/cm$^2$, which is below the threshold value of 0.3 µA/cm$^2$. After 6 days, the Icorr values crossed the threshold value. Thereafter, the Icorr value increased to reach a value of 0.487 µA/cm$^2$ at 31 days. After 397 days, the average corrosion current density (Icorr) value was 0.716 µA/cm$^2$.

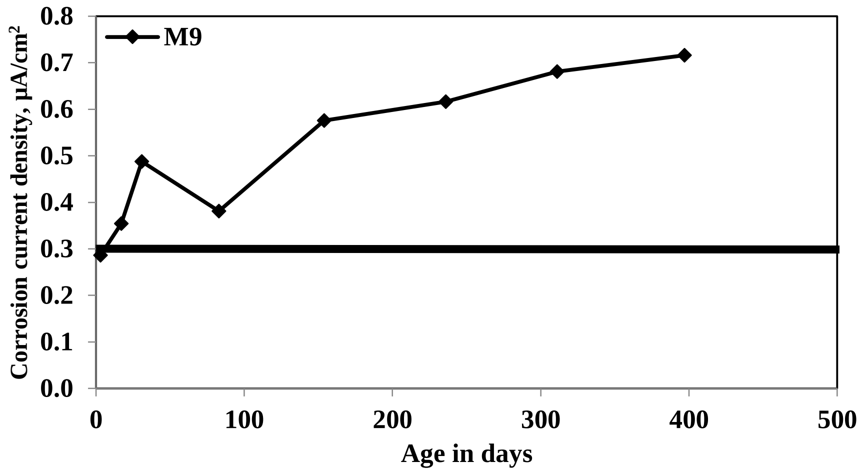


**Figure 4-58: Average Icorr variation in Mix M9.**

### 4.10.10 Limestone and rubber as coarse aggregate and 10% rubber replacing sand

The average corrosion current density (Icorr) values in this concrete mixture are depicted in Figure 4.59. At 3 days, the average Icorr value was 0.249 µA/cm$^2$, which is below the threshold value of 0.3 µA/cm$^2$ for initiation of corrosion. Thereafter, the Icorr value decreased to reach 0.057 µA/cm$^2$ at 83 days. The Icorr value increased to cross the threshold value at 396 days. After 397 days, the average Icorr value was 0.301 µA/cm$^2$.

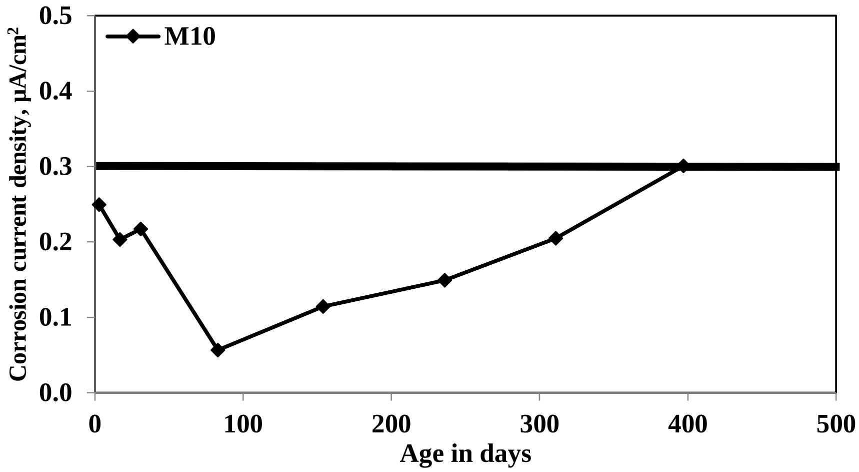


**Figure 4-59: Average Icorr variation in Mix M10.**

# CHAPTER 5

# CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

## 5.1 Conclusions

This research was conducted to produce lightweight concrete utilizing locally available materials, such as scoria, polypropylene, oil ash, crumb rubber and limestone. Several tests were conducted to assess the mechanical, thermal and durability properties of produced concrete. The following conclusions can be drawn based on the data developed in this study:

### 5.1.1 Scoria as coarse aggregate (Mixture M1)

1. The 28 days average unit weight of this concrete, containing 400 kg/m$^3$ cement, 0.4 w/c ratio, 0.5 CA/TA and 0.5 FA/TA, was 1894 kg/m$^3$. This value is lower than 2000 kg/m$^3$, which is the maximum standard limit for concrete to be considered as lightweight.
2. The compressive strength at 28 days was 28.1 MPa, which is higher than the standard compressive strength requirement (17 MPa) for structural LWC. Therefore, this concrete can be used in structural elements.
3. The performance of this concrete in flexure is better than the performance of normal weight concrete. The 28 days modulus of rupture was 5.3 MPa, which is 19% of the compressive strength.

4. The average modulus of elasticity of this concrete at 28 days was 17.86 GPa. Therefore, it has relatively high ductility compared to other concrete mixtures.
5. The thermal conductivity of this concrete was 0.63 W/m.K which is far less than the thermal conductivity of normal weight concrete which is usually between 1.3 to 1.73 W/m.K. Therefore, this concrete has high thermal resistance and can be used as an insulation material.
6. The water absorption of this concrete was 8.85% which is around 1.5 times higher when compared to the water absorption of normal weight concrete.
7. The shrinkage strain crossed the threshold value of 500 microns after 39 days. Hence, the drying shrinkage of this concrete is within the specified limits given by the standards.
8. The 28 days average rapid chloride permeability value of this concrete was 7854 Coulombs. Values more than 4000 Coulombs are considered to be on the higher side. This weakness can be overcome by applying suitable coatings.
9. The corrosion potential of this concrete are higher than the threshold potential value from day 1.
10. The corrosion current density (Icorr) crossed the threshold value of 0.3 μA/cm$^2$ after 212 days of exposure. The time to initiation of corrosion was lesser when compared to normal weight concrete.

### 5.1.2 Scoria as coarse aggregate (Mixture M2)

1. The 28 days average unit weight of this concrete, containing 400 kg/m$^3$ cement, 0.4 w/c ratio, 0.45 CA/TA and 0.55 FA/TA, was 1875 kg/m$^3$. This value is less than 2000

kg/$m^3$, which is the maximum standard limit for concrete to be considered as lightweight.

2. The compressive strength at 28 days was 29.54 MPa, which is more than the standard compressive strength requirement for structural LWC. Therefore, this concrete can be used in structural elements.
3. The performance of this concrete in flexure is better than the performance of normal weight concrete. The 28 days modulus of rupture was 4.66 MPa, which is 16% of the compressive strength.
4. The average modulus of elasticity of this concrete at 28 days was 17.77 GPa. Therefore, it has relatively high ductility compared to other concrete mixtures.
5. The thermal conductivity of this mix was found to be 0.556 W/m.K which is far less than the thermal conductivity of normal weight concrete which is usually between 1.3 to 1.73 W/m.K. Therefore, this concrete has high thermal resistance and can be used as an insulation material.
6. The water absorption of this concrete was 8.61% which is around 1.5 times higher compared to the water absorption of normal weight concrete.
7. The shrinkage strain crossed the threshold value of 500 microns after 15 days. Hence, the drying shrinkage of this concrete is within the specified limits given by the standards.
8. The 28 days rapid chloride permeability value of this concrete was found to be 6048 Coulombs. Values more than 4000 Coulombs are considered to be on the higher side. This weakness can be overcome by applying suitable coatings.

9. The corrosion potential of this concrete are higher than the threshold potential value from day 1.
10. The corrosion current density (Icorr) was more than the threshold value of 0.3 μA/cm$^2$ from the start of exposure.

### 5.1.3 Scoria as coarse aggregate (Mixture M3)

1. The 28 days average unit weight of this concrete, containing 370 kg/m$^3$ cement, 0.4 w/c ratio, 0.45 CA/TA and 0.55 FA/TA, was 1793 kg/m$^3$. This value is less than 2000 kg/m$^3$, which is the maximum standard limit for concrete to be considered as lightweight.
2. The compressive strength at 28 days was 25.56 MPa, which is more than the standard compressive strength requirement for structural LWC. Therefore, this concrete can be used in structural elements.
3. The performance of this concrete in flexure is better than the performance of normal weight concrete. The 28-days modulus of rupture was 4.71 MPa, which is 18.4% of the compressive strength.
4. The average modulus of elasticity of this concrete at 28 days was 20.61 GPa. Therefore, it has relatively high ductility compared to other concrete mixtures.
5. The thermal conductivity of this concrete was 0.56 W/m.K which is far less than the thermal conductivity of normal weight concrete which is usually between 1.3 to 1.73 W/m.K. Therefore, this concrete has high thermal resistance and can be used as an insulation material.

6. The water absorption of this concrete was 7.95% which is around 1.5 times higher compared to the water absorption of normal weight concrete.
7. The shrinkage strain crossed the threshold value of 500 microns after 35 days. Hence, the drying shrinkage of this concrete is within the specified limits given by the standards.
8. The 28 days average rapid chloride permeability value of this concrete was 7163 Coulombs. Values more than 4000 Coulombs are considered to be on the higher side. This weakness can be overcome by applying suitable coatings.
9. The corrosion potential crossed the threshold value of -270 mV SCE after 16 days. Therefore, this concrete is weak in durability properties.
10. The corrosion current density (Icorr) was higher than the threshold value of 0.3 $\mu A/cm^2$ from the start of exposure.

### 5.1.4 Scoria as coarse aggregate and 10% oil ash replacing sand (Mixture M4)

1. The 28 days unit weight of this concrete, containing 370 $kg/m^3$ cement, 0.4 w/c ratio, 0.5 CA/TA and 0.5 FA/TA, was 1891 $kg/m^3$. This value is more than 1840 $kg/m^3$, which is the maximum standard limit for concrete to be considered as lightweight.
2. The compressive strength at 28 days was 23.68 MPa, which is more than the standard compressive strength requirement for structural LWC. Therefore, this concrete can be used in structural elements.
3. The performance of this concrete in flexure is better than the performance of normal weight concrete. The 28 days modulus of rupture was 4.28 MPa, which is 18% of the compressive strength.

4. The average modulus of elasticity of this concrete at 28 days was 16.38 GPa. Therefore, it has relatively high ductility compared to other concrete mixtures.
5. The thermal conductivity of this mix was 0.577 W/m.K which is far less than the thermal conductivity of normal weight concrete which is usually between 1.3 to 1.73 W/m.K. Therefore, this concrete has high thermal resistance and can be used as an insulation material.
6. The water absorption of this concrete was 11.41% which is around 2 times higher when compared to the water absorption of normal weight concrete.
7. The shrinkage strain crossed the threshold value of 500 microns after 6 days. Hence, the drying shrinkage of this concrete is more than the specified limits given by the standards.
8. The 28 days rapid chloride permeability value of this concrete was 10303 Coulombs. Values more than 4000 Coulombs are considered to be on the higher side. This weakness can be overcome by applying suitable coatings.
9. The corrosion potential was above the threshold value of -270 mV SCE from day 1. Therefore, this concrete is weak in durability properties.
10. The corrosion current density (Icorr) crossed the threshold value of 0.3 $\mu A/cm^2$ after just 12 days of exposure.
11. The durability performance of this concrete is weak.

### 5.1.5 Polypropylene as coarse aggregate (Mixture M5)

1. The 28 days unit weight of this concrete, containing 370 $kg/m^3$ cement, 0.4 w/c ratio, 0.5 CA/TA and 0.5 FA/TA, was 1421 $kg/m^3$. This value is in the medium range of standard limits of unit weight for concrete to be considered as lightweight.
2. The compressive strength at 28 days was 16.93 MPa, which is almost similar to the standard compressive strength requirement of 17 MPa for structural LWC.
3. This concrete performed weaker in flexure when compared to performance of normal weight concrete. The 28 days modulus of rupture was 1.75 MPa, which is 10.3% of the compressive strength. Therefore, this type of concrete should not be used in places where there are more tensile stresses involved.
4. The average modulus of elasticity of this concrete at 28 days was 3.95 GPa. Therefore, it has relatively low ductility compared to other concrete mixtures.
5. The thermal conductivity of this mix was 0.338 W/m.K which is far less than the thermal conductivity of normal weight concrete which is usually between 1.3 to 1.73 W/m.K. Therefore, this concrete has high thermal resistance and can be used as an insulation material.
6. The water absorption of this concrete was 6.6% which is around 1.25 times higher compared to the water absorption of normal weight concrete.
7. The shrinkage strain crossed the threshold value of 500 microns after 30 days. Hence, the drying shrinkage of this concrete is within the specified limits given by the standards.

8. The 28 days rapid chloride permeability value of this concrete was 2456 Coulombs. Values between 2000 and 4000 Coulombs are considered to be having moderate chloride permeability.
9. The corrosion potential crossed the threshold value of -270 mV SCE after 5 days.
10. The corrosion current density (Icorr) crossed the threshold value of 0.3 $\mu A/cm^2$ after 278 days of exposure.

### 5.1.6 Polypropylene as coarse aggregate and 10% oil ash replacing sand (Mixture M6)

1. The 28 days average unit weight of this concrete, containing 370 $kg/m^3$ cement, 0.4 w/c ratio, 0.5 CA/TA and 0.5 FA/TA, was 1366 $kg/m^3$. This concrete has the lowest unit weight compared to all other concrete mixtures.
2. The compressive strength at 28 days was 18.78 MPa, which is more than the standard compressive strength requirement of 17 MPa for structural LWC. Therefore, this concrete can be used in structural elements.
3. This concrete performed weaker in flexure when compared to performance of normal weight concrete. The 28 days modulus of rupture was 1.82 MPa, which is 9.7 % of the compressive strength. Therefore, this type of concrete should not be used in places where there are more tensile stresses involved.
4. The average modulus of elasticity of this concrete at 28 days was 4.09 GPa. Therefore, it has relatively high ductility compared to other concrete mixtures.
5. The thermal conductivity of this mix was found to be 0.428 W/m.K which is far less than the thermal conductivity of normal weight concrete which is usually between 1.3

to 1.73 W/m.K. Therefore, this concrete has high thermal resistance and can be used as an insulation material.

6. The water absorption of this concrete was 8.32% which is around 1.5 times higher compared to the water absorption of normal weight concrete.
7. The shrinkage strain crossed the threshold value of 500 microns after 19 days. Hence, the drying shrinkage of this concrete is within the specified limits given by the standards.
8. The 28 days rapid chloride permeability value of this concrete was 3444 Coulombs. Values between 2000 and 4000 Coulombs are considered to be having moderate chloride permeability.
9. The corrosion potential above (more negative) than the threshold value of -270 mV SCE from day 1.
10. The corrosion current density (Icorr) remained below the threshold value of 0.3 $\mu A/cm^2$ even after 397 days of exposure.
11. This concrete performed better in durability and thermal properties compared to the other mixtures but was weaker than other concrete mixtures in terms of mechanical properties. Hence, this concrete can be used in places where durability is of more importance than strength.

### 5.1.7 Scoria and polypropylene as coarse aggregate (Mixture M7)

1. The 28 days average unit weight of this concrete, containing 370 $kg/m^3$ cement, 0.4 w/c ratio, 0.5 CA/TA and 0.5 FA/TA, was 1621 $kg/m^3$. This value is less than 2000

kg/m$^3$, which is the maximum standard limit for concrete to be considered as lightweight.

2. The compressive strength at 28 days was 20.85 MPa, which is more than the standard compressive strength requirement for structural LWC. Therefore, this concrete can be used in structural elements.
3. This concrete performed weaker in flexure when compared to performance of normal weight concrete. The 28 days modulus of rupture was 2.37 MPa, which is 11.4% of the compressive strength. The ratio $f_r/\sqrt{f_c'}$ is 6.25 for this concrete which is 78% of the value of 8 for NWC. Therefore, this type of concrete should not be used in places where there are more tensile stresses involved.
4. The average modulus of elasticity of this concrete at 28 days was 5.62 GPa. Therefore, it has relatively high ductility when compared to other concrete mixtures.
5. The thermal conductivity of this mix was 0.392 W/m.K which is far less than the thermal conductivity of normal weight concrete which is usually between 1.3 to 1.73 W/m.K. Therefore, this concrete has high thermal resistance and can be used as an insulation material.
6. The water absorption of this concrete was 4.84% which is almost equal to water absorption of normal weight concrete.
7. The shrinkage strain crossed the threshold value of 500 microns after 20 days. Hence, the drying shrinkage of this concrete is within the specified limits given by the standards.

8. The 28 days rapid chloride permeability value of this concrete was 4704 Coulombs. Values more than 4000 Coulombs are considered to be on a higher side. This weakness can be overcome by applying suitable coatings.
9. The corrosion potential was above the threshold value of -270 mV SCE from day 1. Therefore, this concrete is weak in durability properties.
10. The corrosion current density (Icorr) crossed the threshold value of 0.3 μA/cm$^2$ after 136 days of exposure.

### 5.1.8 Limestone and polypropylene as coarse aggregate (Mixture M8)

1. The 28 days average unit weight of this concrete, containing 370 kg/m$^3$ cement, 0.4 w/c ratio, 0.5 CA/TA and 0.5 FA/TA, was 1744 kg/m$^3$. This value is less than 2000 kg/m$^3$, which is the maximum standard limit for concrete to be considered as lightweight.
2. The compressive strength at 28 days was 26.53 MPa, which is more than the standard compressive strength requirement for structural LWC. Therefore, this concrete can be used in structural elements.
3. This concrete performed weaker in flexure compared to performance of normal weight concrete. The 28 days modulus of rupture was 2.74 MPa, which is 10.3% of the compressive strength. Therefore, this type of concrete should not be used in places where there are more tensile stresses involved.
4. The average modulus of elasticity of this concrete at 28 days was 7.5 GPa. Therefore, it has relatively high ductility compared to other concrete mixtures.

5. The thermal conductivity of this mix was 0.510 W/m.K which is far less than the thermal conductivity of normal weight concrete which is usually between 1.3 to 1.73 W/m.K. Therefore, this concrete has high thermal resistance and can be used as an insulation material.
6. The water absorption of this concrete was 4.49% which is equal to the water absorption of normal weight concrete.
7. The shrinkage strain crossed the threshold value of 500 microns after 26 days. Hence, the drying shrinkage of this concrete is within the specified limits given by the standards.
8. The 28 days average rapid chloride permeability value of this concrete was 2731 Coulombs. Values in the range of 2000 to 4000 Coulombs are considered to perform moderately in terms of chloride permeability.
9. The corrosion potential was above the threshold value of -270 mV SCE from day 1. Therefore, this concrete is weak in durability properties.
10. The corrosion current density (Icorr) value crossed the threshold value of 0.3 $\mu A/cm^2$ after 137 days of exposure.
11. This concrete can be considered optimum among all the mixtures in terms of mechanical, thermal and durability properties.

### 5.1.9 Scoria as coarse aggregate and 10% rubber replacing sand (Mixture M9)

1. The 28 days average unit weight of this concrete, containing 370 $kg/m^3$ cement, 0.4 w/c ratio, 0.5 CA/TA and 0.5 FA/TA, was 1809 $kg/m^3$. This value is less than 2000

kg/$m^3$, which is the maximum standard limit for concrete to be considered as lightweight.

2. The compressive strength at 28 days was 19.53 MPa, which is more than the standard compressive strength requirement for structural LWC. Therefore, this concrete can be used in structural elements.
3. The performance of this concrete in flexure is better than the performance of normal weight concrete. The 28 days modulus of rupture of M1 was 3.21 MPa, which is 16.4% of the compressive strength.
4. The average modulus of elasticity of this concrete at 28 days was 12.77 GPa. Therefore, it has relatively moderate ductility compared to other concrete mixtures.
5. The thermal conductivity of this mix was 0.544 W/m.K which is far less than the thermal conductivity of normal weight concrete which is usually between 1.3 to 1.73 W/m.K. Therefore, this concrete has high thermal resistance and can be used as an insulation material.
6. The water absorption of this concrete was found to be 9.08% which is around 2 times more compared to the water absorption of normal weight concrete.
7. The shrinkage strain crossed the threshold value of 500 microns after 61 days. Hence, the drying shrinkage of this concrete is much within the specified limits given by the standards.
8. The 28 days average rapid chloride permeability value of this concrete was 6191 Coulombs. Values above 4000 Coulombs are considered to have chloride permeability value on a higher side. This weakness can be overcome by applying suitable coatings.

9. The corrosion potential was above the threshold value of -270 mV SCE from day 1. Therefore, this concrete is weak in durability properties.

10. The corrosion current density (Icorr) value crossed the threshold value of 0.3 μA/cm$^2$ after just 6 days of exposure.

### 5.1.10 Limestone as coarse aggregate and 10% rubber replacing sand (Mixture M10)

1. The 28 days average unit weight of this concrete, containing 370 kg/m$^3$ cement, 0.4 w/c ratio, 0.5 CA/TA and 0.5 FA/TA, was 2140 kg/m$^3$. This value is more than 2000 kg/m$^3$, which is the maximum standard limit for concrete to be considered as lightweight. This concrete cannot be considered as LWC.

2. The compressive strength at 28 days was 20.34 MPa, which is more than the standard compressive strength requirement for structural LWC. Therefore, this concrete can be used in structural elements.

3. This concrete performed weaker in flexure when compared to performance of normal weight concrete. The 28 days modulus of rupture was 2.81 MPa, which is 13.8% of the compressive strength. Therefore, this type of concrete should not be used in places where there are more tensile stresses involved.

4. The average modulus of elasticity of this concrete at 28 days was 14.66 GPa. Therefore, it has a relatively moderate ductility compared to other concrete mixtures.

5. The thermal conductivity of this mix was 0.706 W/m.K which is far less than the thermal conductivity of normal weight concrete which is usually between 1.3 to 1.73 W/m.K. Therefore, this concrete has high thermal resistance and can be used as an insulation material.

6. The water absorption of this concrete was 3.35% which is less than the water absorption of normal weight concrete.
7. The shrinkage strain crossed the threshold value of 500 microns after 24 days. Hence, the drying shrinkage of this concrete is within the specified limits given by the standards.
8. The 28 days rapid chloride permeability value of this concrete was 3687 Coulombs. Values in the range of 2000 to 4000 Coulombs are considered to have chloride permeability value in the moderate range.
9. The corrosion potential was above the threshold value of -270 mV SCE from day 1.
10. The corrosion current density (Icorr) value crossed the threshold value of 0.3 $\mu A/cm^2$ after 396 days of exposure.
11. This concrete has good durability properties.

## 5.2 Recommendations

The Table 5.1 summarizes the avenues for utilization of the developed concrete with the selected local materials.

**Table 5-1: Avenues for utilization of developed LWC**

| Concrete | Applications |
|---|---|
| Scoria as coarse aggregate (M1) | High strength lightweight structural concrete with high corrosion resistance requirements. |
| Scoria as coarse aggregate (M2) | High strength lightweight structural concrete with low corrosion resistance requirements. |
| Scoria as coarse aggregate (M3) | Medium strength lightweight structural concrete with moderate corrosion resistance requirements. |
| Scoria as coarse aggregate and 10% oil ash replacing sand (M4) | Medium strength lightweight concrete with high corrosion resistance requirements. |
| Polypropylene as coarse aggregate (M5) | Low strength lightweight concrete with high corrosion resistance requirements. |
| Polypropylene as coarse aggregate and 10% oil ash replacing sand (M6) | Low strength lightweight concrete with high corrosion resistance requirements. |
| Scoria and polypropylene as coarse aggregate (M7) | Low strength lightweight concrete with moderate corrosion resistance requirements. |
| Limestone and polypropylene as coarse aggregate (M8) | Medium strength lightweight structural concrete with moderate corrosion resistance requirements. |
| Scoria as coarse aggregate and 10% rubber replacing sand (M9) | Low strength lightweight concrete with low corrosion resistance requirements. |
| Limestone as coarse aggregate and 10% rubber (M10) | Low strength lightweight concrete with high corrosion resistance requirements. |

## 5.3 Future Research

Following are the recommendations for future research.

- Investigate other lightweight materials for structural lightweight concrete.
- Evaluate the performance of lightweight concrete with mineral additives.
- Develop long-term data for a better prediction of durability of lightweight concrete with local materials.

# REFERENCES


[1] Z. Li, Z. Ding, and Y. Zhang, “Development of Sustainable Cementitious Material,” in *International Workshop on Sustainable Development and Concrete Technology*, 2004, pp. 55–76.

[2] S. Mindess, F. Young, and D. Darwin, *Concrete*, 2nd ed. New Jersey: Prentice Hall, Pearson Education, Inc. Upper Saddle River, NJ 07458, U.S.A., 2003, p. 644.

[3] B. H. Spratt, *The Structural Use of Lightweight Aggregate Concrete*. Cement and Concrete Association, 1974.

[4] M. K.F. and L. F. Kahn, “Lightweight Concrete Reduces Weight and Increases Span Length of Pretensioned Bridge Girders,” *PCI J.*, vol. 47, no. 1, pp. 68–75, 2002.

[5] C. J. Waldron, T. E. Cousins, A. J. Nassar, and J. P. Gomez, “Demonstration of Use of High-Performance Lightweight Concrete in Bridge Superstructure in Virginia,” *J. Perform. Constr. Facil. ASCE*, vol. 19, no. 2, pp. 146–154, 2005.

[6] N. 18-15, “High-Performance/High-Strength Lightweight Concrete for Bridge Girders and Decks,” 2008.

[7] M. . Moufti, A. . Sabtan, O. . El-Mahdy, and W. . Shehata, “Assessment of the Industrial Utilization of Scoria Materials in Central Harrat Rahat, Saudi Arabia,” *Eng. Geol.*, vol. 57, no. 3–4, pp. 155–162, Jul. 2000.

[8] A. Kılıç, C. D. Atiş, E. Yaşar, and F. Özcan, “High-Strength Lightweight Concrete made with Scoria Aggregate Containing Mineral Admixtures,” *Cem. Concr. Res.*, vol. 33, no. 10, pp. 1595–1599, Oct. 2003.

[9] “U.S. Energy Information System,” *Ctry. Anal. Briefs*, 2011.

[10] T. Y. Lo and H. Z. Cui, “Properties of Green Lightweight Aggregate Concrete,” in *International workshop on sustainable development and concrete technology*, 2002, pp. 113–8.

[11] N. A. Libre, M. Shekarchi, M. Mahoutian, and P. Soroushian, “Mechanical Properties of Hybrid Fiber Reinforced Lightweight Aggregate Concrete made with Natural Pumice,” *Constr. Build. Mater.*, vol. 25, no. 5, pp. 2458–2464, May 2011.

[12] A. M. Neville and J. J. Brooks, *Concrete Technology*. Malaysia: Pearson Education Asia Pte Ltd, PP(CTP), 2008.

[13] *CEB/FIP Manual of Design and Technology*. Great Britain: Lightweight Aggregate Concrete. First Pub., 1977.

[14] O. A. Duzgun, R. Gul, and A. C. Aydin, "Effect of Steel Fibers on the Mechanical Properties of Natural Lightweight Aggregate Concrete," vol. 59, pp. 3357–3363, 2005.

[15] V. Sussman, "Lightweight Plastic Aggregate Concrete," *JA Conc Inst Proc*, vol. 72, pp. 32–3, 1975.

[16] C. L. Verma, S. K. Handa, S. K. Jain, and R. K. Yadav, "Techno-Commercial Perspective Study for Sintered Fly Ash Light-weight Aggregates in India," *Constr Build Mater*, vol. 12, no. 6–7, pp. 341–6, 1998.

[17] S. K. Najamuddin, "Production of Medium to Low Strength Concrete Utilizing Indigenous Waste Products," KFUPM, 2011.

[18] D. S. Babu, K. G. Babu, and T. H. Wee, "Properties of Lightweight Expanded Polystyrene Aggregate Concretes Containing Fly Ash," vol. 35, pp. 1218–1223, 2005.

[19] "ACI Report on Early-Age Cracking: Causes, Measurement and Mitigation," Farmington Hills, MI, 2010.

[20] K. Kovler and O. M. Jensen, Eds., "RILEM Report 41. Internal Curing of Concrete – State of the Art.," 2007, p. 161.

[21] P. Klieger, "Early High Strength Concrete for Prestressing," in *World Conference on Prestressed Concrete*, 1957.

[22] D. L. Bloem, "Concrete Strength Measurements – Cores and Cylinders," *ASTM Proceedings, Philadelphia, PA*, vol. 65, 1965.

[23] R. Philleo, "Concrete Science and Reality," in *Materials science of concrete II*, 1991.

[24] T. A. Holm, O. S. Ooi, and T. W. Bremner, "Moisture Dynamics in Lightweight Aggregate and Concrete," *Expand. Shale Clay Slate Institute, Publ. # 9340*, p. 12, 2004.

[25] D. P. Bentz and K. A. Snyder, “Protected Paste Volume in Concrete: Extension to Internal Curing using Saturated Lightweight Fine Aggregate,” *Cem Concr Res*, vol. 29, no. 11, pp. 1863–7, 1999.

[26] O. M. Jensen and P. F. Hansen, “Water-entrained Cement-based Materials: I. Principles and Theoretical Background,” *Cem Concr Res*, vol. 31, no. 4, pp. 647–54, 2001.

[27] J. Schlitter, “New Methods to Quantify the Cracking Performance of Cementitious Systems made with Internal Curing,” Purdue University, 2010.

[28] C. C. Yang and R. Huang, “A Two-phase Model for Predicting the Compressive Strength of Concrete,” *Cem Concr Res*, vol. 26, no. 10, pp. 1567–77, 1996.

[29] F. D. Lydon, *Concrete Mix Design*, 2nd ed. London: Applied Science Publishers, 1982.

[30] T. W. Bremner and T. A. Holm, “Elasticity, Compatibility and the Behavior of Concrete,” *ACI Mater J*, vol. 83, no. 2, pp. 244–50, 1986.

[31] R. Wasserman and A. Bentur, “Effect of Lightweight Fly Ash Aggregate Microstructure on the Strength of Concrete,” *Cem Concr Res*, vol. 27, no. 4, pp. 525–37, 1997.

[32] H. E. Vivian, “The Effect of Void Space on Mortar Expansion,” *Commonw. Aust. CSIR Bull. No. 229*, vol. 3, pp. 47–54, 1947.

[33] B. Zatler and E. Mali, “Alkali–Aggregate Reaction in Lightweight Concrete,” in *6th International Conference—Alkalis in Concrete Research and Practice—Proceedings*, 1983, pp. 495–503.

[34] L. De Ceukelaire, “Alkali– Silica Reaction in a Lightweight Concrete Bridge,” in *Proc. of the 9th International Conference on Alkali–Aggregate Reaction in Concrete*, 1992, pp. 231–239.

[35] C. F. Crumpton, “Lightweight Aggregate Concrete Sometimes Grows. Blame ASR if it is the most Likely Cause,” *Concr. Constr.*, vol. 33, no. 6, pp. 618–619, 1988.

[36] R. J. Collins and P. D. Bareham, “Alkali–Silica Reaction: Suppression of Expansion Using Porous Aggregate,” *Cem. Concr. Res.*, vol. 17, no. 1, pp. 89–96, 1987.

[37] J. W. Figg, “Reaction Between Cement and Artificial Glass in Concrete,” in *Proc. 5th International Conference on AAR in Concrete*, p. S 252/7.

[38] K. Hossain, “Properties of Volcanic Ash and Pumice Concrete,” Zurich, Switzerland, 1999.

[39] K. Hossain, “Properties of Volcanic Scoria Based Lightweight Concrete,” *Concr Res*, vol. 56, no. 2, pp. 111–20, 2002.

[40] S. H. Kostmatka, B. Kerkhoff, W. C. Panarese, N. F. Macleod, and R. J. McGrath, *Design and Control of Concrete Mixtures*, 7th Canadi. Cement Association of Canada, 2002.

[41] M. Singh and M. Garg, “Perlite-based Building Materials – A Review of Current Applications,” *Constr Build Mater*, vol. 5, no. 2, pp. 75–81, 1991.

[42] K. Kohno, T. Okamoto, Y. Isikawa, T. Sibata, and H. Mori, “Effects of Artificial Lightweight Aggregate on Autogenous Shrinkage of Concrete,” *Cem Concr Res*, vol. 29, no. 4, pp. 611–4, 1999.

[43] H. Al-Khaiat and M. Haque, “Effect of Initial Curing on Early Strength and Physical Properties of a Lightweight Concrete,” *Cem Concr Res*, vol. 28, no. 6, pp. 859–966, 1998.

[44] A. Bouguerra, A. Ledhem, F. de Barquin, R. Dheilly, and M. Queneudec, “Effect of Microstructure on the Mechanical and Thermal Properties of Lightweight Concrete Prepared from Clay, Cement, and Wood Aggregate,” *Cem Concr Res*, vol. 28, no. 8, pp. 1179–90, 1998.

[45] K. Hossain, “Blended Cement Using Volcanic Ash and Pumice,” *Cem Concr Res*, vol. 33, no. 10, pp. 1601–5, 2003.

[46] K. Hossain and M. Lachemi, “Development of Volcanic Ash Concrete: Strength, Durability and Micro-structural Investigations,” *ACI Mater J*, vol. 103, no. 1, pp. 11–7, 2003.

[47] A. Neville, *Properties of Concrete*, 4th ed. Harlow, England: Longman Group Ltd., 1995.

[48] R. Demirbogˇa, I. O¨ ru¨ ng, and R. Gu¨ l, “Effects of Expanded Perlite and Mineral Admixtures on the Compressive Strength of Low-Density,” *Cem. Concr. Res.*, vol. 31, pp. 1627–1632, 2001.

[49] M. S. Akman, *Construction Materials (YapN Malzemeleri)*, 2nd ed. Istanbul, 1990, p. 162.

[50] B. PostacNogˇlu, *Concrete (Beton)*. Istanbul, 1987, p. 404.

[51] A. A. Shehata and W. M. Sabtan, “Evaluation of Engineering Properties of Scoria in Central Harrat Rahat , Saudi Arabia,” no. March, pp. 219–225, 2000.

[52] A. A. Arakelyan and M. G. Ter-Oganyan, “Effectiveness of Using Lightweight Natural Aggregates in Hydraulic Construction,” no. 6, pp. 26–28, 1967.

[53] A. A. Arakelyan, “Basic Properties of Concrete for Hydraulic Construction made of Lithoid Pumice,” in *Concrete made of Lithoid Pumice*, 1958.

[54] A. A. Arakelyan, “Use of Lightweight Concretes with Natural Aggregate in Hydraulic Structures,” in *Sixth Conference of Concrete and Reinforced Concrete of the Armenian Administration of the Scientific and Technical Department of the Building Industry and AISM of Gosstroi*, 1966.

[55] F. Sajedi and P. Shafigh, “High-Strength Lightweight Concrete Using Leca, Silica Fume, and Limestone,” *Arab. J. Sci. Eng.*, vol. 37, no. 7, pp. 1885–1893, Apr. 2012.

[56] Y. W. Choi, Y. J. Kim, H. C. Shin, and H. Y. Moon, “An Experimental Research on the Fluidity and Mechanical Properties of High-strength Lightweight Self-compacting Concrete,” *Cem. Concr. Res.*, vol. 36, pp. 1595–1602, 2006.

[57] “Alternative Cementitious Materials,” Dhahran, 2010.

[58] J. Camilleri, M. Anastasi, and A. Torpiano, “The Microstructure and Physical Properties of Heavy Oil Fuel Ash Replaced Portland Cement for Use in Flowable Fill Concrete and the Production of Concrete Masonry Units,” *Constr. Build. Mater.*, vol. 38, pp. 970–979, Jan. 2013.

[59] “The Use of GGBS and PFA in Concrete,” Slough (UK), 1991.

[60] G. A. Habeeb and H. B. Mahmud, “Pozzolans for Sustainable Concrete – A Review,” in *International conference for technical postgraduates (TECHPOS). Towards advancement of engineering research – global challenges*, 2009.

[61] M. A. Daous, “Utilization of Cement Kiln Dust and Fly Ash in Cement Blends in Saudi Arabia,” *JKAU Eng Sci*, vol. 15, pp. 33–45, 2004.

[62] H. Y. Kew, R. Cairns, and M. J. Kenny, “The Use of Recycled Rubber Tyres in Concrete,” in *Proceedings of the International Conference on Sustainable Waste Management and Recycling*, 2004, pp. 135–142.

[63] G. Wang, B. Zhang, Z. Shui, D. Tang, and Y. Kong, “Experimental Study on the Performance and Microstructure of Rubberized Lightweight Aggregate Concrete,” *Prog. Rubber, Plast. Recycl. Technol.*, vol. 28, no. 4, pp. 147–156, 2012.

[64] B. S. Mohammed, K. M. Anwar Hossain, J. T. Eng Swee, G. Wong, and M. Abdullahi, “Properties of crumb rubber hollow concrete block,” *J. Clean. Prod.*, vol. 23, no. 1, pp. 57–67, Mar. 2012.

[65] H. Wang, B. Chen, and Y. Wu, “A Study of the Fresh Properties of Controlled Low-Strength Rubber Lightweight Aggregate Concrete ( CLSRLC ),” vol. 41, pp. 526–531, 2013.

[66] C. E. Pierce and M. C. Blackwell, “Potential of Scrap Tire Rubber as Lightweight Aggregate in Flowable Fill.,” *Waste Manag.*, vol. 23, no. 3, pp. 197–208, Jan. 2003.

[67] J. Wang, Y. Li, and M. Z. Zhang, “Shrinkage Performance and Cracking Resistance Mechanism of Rubberized Lightweight Aggregate Concrete with Polymer,” *Key Eng. Mater.*, vol. 385–387, pp. 817–820, 2008.

[68] Y. Farnam, M. Mahoutian, S. Mohammadi, and M. Shekarchi, “Experimental and Numerical Studies of Impact Behavior of Fiber Lightweight Aggregate Concrete,” in *Proceedings of the Structures Congress- Crossing the Borders*, 2008, p. 314.

[69] ASTM C 39, “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens,” in *Annual Book of ASTM Standards, Vol 04.02*, West Conshohocken, PA 19428-2959, United States, 2003.

[70] ASTM C 1202, “Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration,” in *Annual Book of ASTM Standards, Vol 04.02*, West Conshohocken, PA 19428-2959, United States, 1997.

[71] ASTM C 876, “Standard Test Method for Half-cell Potentials of Uncoated Reinforcing Steel in Concrete,” in *Annual Book of ASTM Standards, Vol 04.02*, West Conshohocken, PA 19428-2959, United States, 2005.

[72] M. Stern and A. L. Geary, “A Theoretical Analysis of the Slope of the Polarization Curves,” *J. Electrochem. Soc.*, vol. 104, p. 56, 1957.

[73] C. Andrade, “Determination of the Corrosion Rate of Steel Embedded in Concrete,” *ASTM Special Technical Publication STP 906*, Philadelphia, p. 43, 1986.

[74] P. Lambert, C. L. Page, and P.R.W. Vassie, “Investigations of Reinforcement Corrosion: Electrochemical Monitoring of Steel in Chloride-Contaminated Concrete,” *Mater. Struct.*, vol. 24, pp. 351–358, 1991.

[75] ASTM C 642, “Standard Test Method for Density, Absorption, and Voids in Hardened Concrete,” in *Annual Book of ASTM Standards, Vol 04.02,* West Conshohocken, PA 19428-2959, United States, 1997.

[76] ASTM C 78, “Standard Test Method for Flexural Strength of Concrete,” in *Annual Book of ASTM Standards, Vol 04.02,* West Conshohocken, PA 19428-2959, United States, 2002.

[77] ASTM C 157, “Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete,” in *Annual Book of ASTM Standards, Vol 04.02,* West Conshohocken, PA 19428-2959, United States, 2003.

[78] ASTM C 201, “Standard Test Method for Thermal Conductivity of Refractories,” in *Annual Book of ASTM Standards, Vol 04.02*, West Conshohocken, PA 19428-2959, United States, 2009.

[79] ASTM C 469, “Standard Test Method for Static Modulus of Elasticity and Poisson’s Ratio of Concrete in Compression,” in *Annual Book of ASTM Standards, Vol 04.02,* West Conshohocken, PA 19428-2959, United States, 2002.

[80] ASTM C 567, “Standard Test Method for Determining Density of Structural Lightweight Concrete,” in *Annual Book of ASTM Standards, Vol 04.02,* West Conshohocken, PA 19428-2959, United States, 2000.

# VITAE

**Name** : Osman Mohammed Saber

**Nationality** : Indian

**Date of Birth** : 4th November, 1989

**Permanent Address** : H. No.: 11-4-614/6,

Jaweed Manzil, Bazarguard,

Hyderabad – 500004, Andhra Pradesh, INDIA.

**Email** : osman.saber20@gmail.com

**Phone** : +966-552118283

**Degrees:**

**Bachelor of Engineer** in Civil Engineering from Osmania University (Sept. 2007 – April 2011).

**Experience:**

**Research Assistant** in Civil Engineering Department of King Fahd University of Petroleum & Minerals (KFUPM) (Dec 2011 – July 2014).

**Workshops:**

- Concrete Deterioration and its Prevention (May 2013).
- Workshop on applications of ABAQUS (Nov 2012).